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Abstract

Hunsaker and Savelsbergh [Operations Research Letters 30, 2002] discussed feasibility testing for a dial-a-ride problem under maximum wait time and maximum ride time constraints. We show that this feasibility test can be expressed as a shortest path problem in vertex-weighted interval graphs, which leads to a simple linear time algorithm.

Keywords: Dial-a-ride; feasibility check; shortest path; difference constraint system.

1 Introduction

Dial-a-ride problems concern the dispatching of a vehicle to satisfy requests where an item (or a person) has to be picked up from a specific location and has to be delivered to some other specific location. Dial-a-ride problems arise in many practical application areas, as for instance shared taxi services, courier services, and transportation of elderly and disabled persons.

Hunsaker & Savelsbergh [4] analyzed the following feasibility question for a dial-a-ride problem arising in a taxi company: An instance specifies a sequence of $2n+1$ events that have to be served (one after the other and in the given order) by a single vehicle. The first event is the dispatch of the vehicle from a central facility. The remaining $2n$ events are grouped into a set $\mathcal{P}$ of pairs (i, j) with $i < j$. In every pair (i, j) the earlier event i is the pickup and the later event j is the delivery of some fixed item (we stress that the two events in such a pair are not necessarily consecutive in the event sequence). The problem consists in deciding whether there exist $2n+1$ time points for these $2n+1$ events subject to the following three families of constraints.

Time windows: The ith event ($1 \le i \le 2n+1$) must occur during a pre-specified time window between time points α_i and β_i with $\alpha_i \le \beta_i$.

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Riding times: The riding time from the ith to the $(i+1)$th event $(1 \le i \le 2n)$ is $\gamma_{i,i+1}$. For every pickup and delivery pair $(i,j) \in \mathcal{P}$, the time from pickup to delivery can be at most $\delta_{i,j} > 0$ time units.

Waiting times: At the ith pickup or delivery location $(2 \le i \le 2n+1)$, the vehicle can wait for at most ω_i times units before departing.

We note that there are three points in which our problem description deviates from the one by Hunsaker & Savelsbergh [4]. First, our riding time bounds $\delta_{i,j}$ can be arbitrary numbers, whereas the riding time bounds in [4] are proportional to the distances between pickup location and delivery location. In this respect, our model is slightly more general and contains the model in [4] as a special case. Secondly, our waiting time bounds ω_i depend on the event, whereas the waiting time bounds in [4] all are identical. Again this is a slight extension of the model in [4], which also is mentioned in the discussion section of [4]. Thirdly, the problem in [4] also incorporates item sizes and a capacity bound for the vehicle. These capacity constraints are independent of the timing and riding constraints, and they can be checked separately in $O(n)$ overall time. This independent subproblem has been discussed and settled in [4], and there is no reason for re-discussing it here.

Hunsaker & Savelsbergh [4] design a sophisticated linear time algorithm that tests for the existence of a schedule that satisfies the three constraint families listed above. Tang, Kong, Lau & Ip [5] identify a crucial gap in the algorithm of [4], and they also provide a concrete counter-example where the algorithm declares a feasible instance to be infeasible. As a partial repair [5] provides another algorithm for the problem with a weaker quadratic running time $O(n^2)$. We note that such a quadratic running time is too slow for practical applications: The feasibility test shows up as a subproblem in improvement-based algorithms, and has to be performed many times.

Contribution of this note. We formulate the dial-a-ride feasibility test of [4] as a system of linear inequalities (Sections 3 and 4), which by standard methods can be rewritten into a system of difference constraints (Section 5). By carefully analyzing the structure of these difference constraints (Section 6), we then transform the problem into a shortest path problem in a vertex-weighted interval graph. All in all, this yields the desired linear time $O(n)$ algorithm for the feasibility test.

2 Preliminaries

Suppose that $\alpha_{i+1} < \alpha_i$ for some i with $1 \le i \le 2n$. Since the vehicle cannot serve the ith event before time α_i, it cannot arrive at the $(i+1)$th location before time α_i. Hence we may update the data as $\alpha_{i+1} := \alpha_i$. All updates (for all values of i) can be performed by a single $O(n)$ time pass over the locations in increasing order of i. A symmetric argument shows that whenever $\beta_{i+1} < \beta_i$ holds for some i with $1 \le i \le 2n$, then we may update $\beta_i := \beta_{i+1}$. Furthermore, all such updates can be done during a single $O(n)$ time pass over the locations in decreasing order of i.

Therefore we assume throughout that the left and right endpoints of the time intervals form two non-decreasing sequences $\alpha_1 \le \alpha_2 \le \cdots \le \alpha_{2n+1}$ and $\beta_1 \le \beta_2 \le \cdots \le \beta_{2n+1}$.

3 Linear equations and inequalities

We formulate the dial-a-ride problem as a system of linear equations and inequalities. The ith event ($1 \le i \le 2n+1$) is described by three real variables: The arrival time A_i and the departure time D_i of the vehicle at the location of the ith event, and the time point E_i at which the actual pickup/delivery occurs. For the first event, we identify the variables E_1 and D_1 so that they coincide with the dispatch time of the vehicle from the central facility.

$$A_1 = \alpha_1 \quad \text{and} \quad E_1 = D_1 \tag{1}$$

Clearly the ith event must fit between the arrival and the departure time of the vehicle.

$$A_i \ \le\ E_i \ \le\ D_i \qquad\qquad \text{for } i = 2, \ldots, 2n+1. \tag{2}$$

Now let us express the constraints of the problem. The ith event must occur during its time window $[\alpha_i, \beta_i]$.

$$\alpha_i \ \le\ E_i \ \le\ \beta_i \qquad\qquad \text{for } i = 1, \ldots, 2n+1. \tag{3}$$

The riding time $\gamma_{i,i+1}$ from the ith to the $(i+1)$th event yields

$$A_{i+1} \ = \ D_i + \gamma_{i,i+1} \qquad\qquad \text{for } i = 1, \ldots, 2n. \tag{4}$$

For every pickup and delivery pair $(i, j) \in \mathcal{P}$, the time from pickup to delivery is constrained by

$$E_j \ \le\ E_i + \delta_{i,j} \qquad\qquad \text{for all pairs } (i, j) \in \mathcal{P}. \tag{5}$$

Finally, the waiting time constraints yield

$$D_i \ \le\ A_i + \omega_i \qquad\qquad \text{for } i = 2, \ldots, 2n+1. \tag{6}$$

The dial-a-ride instance has a feasible solution, if and only if the linear system (1)–(6) with $O(n)$ constraints has a feasible solution over the real numbers.

4 More linear inequalities

Our next step is to rewrite the system (1)–(6) into an equivalent but simpler system centered around a new set of variables: For $i = 1, \ldots, 2n+1$ we introduce the non-negative variable x_i to measure the total waiting time between time point α_1 and time point D_i (that is, the total time that the vehicle did not spent on driving before departing from the ith location). Furthermore, for $1 \le i \le j \le 2n+1$ we introduce the constant Γ_i to denote the overall riding time to move through the locations $1, 2, \ldots, i$.

$$\Gamma_i \;=\; \sum_{k=1}^{i-1} \gamma_{k,k+1}.$$

Then the arrival times $A_2, \ldots, A_{2n+1}$ and the departure times $D_1, \ldots, D_{2n+1}$ can be rewritten as

$$A_i = x_{i-1} + \Gamma_i \qquad \text{and} \qquad D_i = x_i + \Gamma_i. \tag{7}$$

Each of the events $E_2, \ldots, E_{2n+1}$ is either a pickup or a delivery that is constrained by (2), (3), and (5). Hence it must occur between the lower bound $\max\{A_i, \alpha_i\}$ and the upper bound $\min\{D_i, \beta_i\}$. The resulting interval is non-empty, if and only if $A_i \le D_i$ and $A_i \le \beta_i$ and $\alpha_i \le D_i$ hold. Thus Fourier-Motzkin elimination of E_i yields for $i = 2, \ldots, 2n+1$ the constraints

$$x_{i-1} \le x_i \qquad \text{and} \qquad x_{i-1} \le \beta_i - \Gamma_i \qquad \text{and} \qquad \alpha_i - \Gamma_i \le x_i. \tag{8}$$

If the ith event is a pickup, then we may delay it as much as possible by setting $E_i := \min\{D_i, \beta_i\}$. If the jth event is a delivery, then we may schedule it as early as possible and set $E_j := \max\{A_j, \alpha_j\}$. Then (5) means for every pickup and delivery pair $(i, j) \in \mathcal{P}$ the four conditions that $A_j \le D_i + \delta_{i,j}$, that $A_j \le \beta_i + \delta_{i,j}$, that $\alpha_j \le D_i + \delta_{i,j}$, and that $\alpha_j \le \beta_i + \delta_{i,j}$. The last condition does not depend on any variable (and if it is violated, then the system is trivially infeasible). The other three conditions yield the following constraints.

$$x_{j-1} \;\le\; x_i + \delta_{i,j} + \Gamma_i - \Gamma_j \qquad \text{for all } (i,j) \in \mathcal{P} \tag{9}$$

$$x_{j-1} \;\le\; \beta_i + \delta_{i,j} - \Gamma_j \qquad \text{for all } (i,j) \in \mathcal{P} \tag{10}$$

$$\alpha_j - \delta_{i,j} - \Gamma_i \;\le\; x_i \qquad \text{for all } (i,j) \in \mathcal{P} \tag{11}$$

The remaining constraints (1), (4), (6) are handled as follows. Constraints (1) and (3) yield

$$0 \;\le\; x_1 \;\le\; \beta_1 - \alpha_1. \tag{12}$$

Constraint (4) is satisfied because of (7), and becomes vacuous. Finally the waiting time constraints (6) translate into

$$x_i \;\le\; x_{i-1} + \omega_i \qquad \text{for } i = 2, \ldots, 2n+1. \tag{13}$$

The dial-a-ride instance has a feasible solution, if and only if the linear system (8)–(13) with $O(n)$ constraints has a feasible solution over the real numbers.

5 Difference constraint systems

Every inequality in (8)–(13) is either an upper bound constraint $x_i \le U_i$, or a lower bound constraint $L_i \le x_i$, or a difference constraint $x_j - x_i \le D_{i,j}$. By applying a standard trick, we will now transform all upper and lower bound constraints into difference constraints.

For this purpose, we introduce two new variables x_0 and x_{2n+2}. Variable x_0 represents the value 0, and hence is a lower bound on all other variables. Variable x_{2n+2} represents the value $K := \beta_{2n+1} - \alpha_1$, and hence is an upper bound for all other variables. We create the two new constraints

$$x_{2n+2} - x_0 \le K \qquad \text{and} \qquad x_0 - x_{2n+2} \le -K, \tag{14}$$

which together enforce $x_{2n+2} - x_0 = K$. Every upper bound constraint $x_i \le U_i$ in (8)–(13) is replaced by a corresponding constraint

$$x_i - x_0 \ \le \ U_i. \tag{15}$$

Every lower bound constraint $L_i \le x_i$ in (8)–(13) is replaced by a corresponding constraint

$$x_{2n+2} - x_i \ \le \ K - L_i. \tag{16}$$

We will refer to (14), to the new difference constraints (15) and (16), and to the old difference constraints in (8), (9), (13) short as the difference constraint system DCS.

Lemma 1 *The following four statements are pairwise equivalent.*

(i) The original dial-a-ride instance has a feasible solution.

(ii) The system (8)–(13) has a feasible solution over the real numbers.

(iii) DCS has a feasible solution with $x_0 = 0$ and $x_{2n+2} = K$.

(iv) DCS has a feasible solution.

There is a close connection between difference constraint systems and negative-weight cycles in directed graphs; see for instance Section 24.4 of Cormen, Leiserson, Rivest & Stein [2]. We create for every variable x_i ($0 \le i \le 2n+2$) a corresponding vertex i. We create for every difference constraint $x_j - x_i \le D_{i,j}$ an arc from vertex i to vertex j with weight $D_{i,j}$. It is well-known and easy to see (see for instance Theorem 24.9 in [2]) that the underlying difference constraint system has a feasible solution, if and only if the corresponding directed graph G does not contain any negative-weight cycles.

In our case, the directed graph G has $O(n)$ vertices and $O(n)$ arcs. Hence a straightforward application of the Bellman-Ford algorithm or of the Goldberg-Radzik algorithm would yield an $O(n^2)$ time feasibility test.

6 A linear time feasibility test

To get a linear time algorithm, we look a little bit deeper into the structure of DCS and the corresponding directed graph G. A difference constraint $x_j - x_i \leq D_{i,j}$ is a *forward* constraint (and the corresponding arc $i \to j$ is a forward arc), if $i < j$ holds. Otherwise we are dealing with a *backward* constraint (and a corresponding backward arc). Now let us go through all constraints in DCS.

- The difference constraints in (8) are of the form $x_{i-1} - x_i \leq 0$. They are backward constraints, and their arc weights are always zero.
- The constraints in (9) are forward constraints. If $\delta_{i,j} < \Gamma_j - \Gamma_i$ then the system is infeasible. Hence we may assume that all corresponding arc weights are non-negative.
- The constraints (13) are forward constraints, and the corresponding arc weights ω_i are non-negative.
- In (14) we have one forward constraint with positive arc weight, and one backward constraint with negative arc weight.
- The difference constraints in (15) arise from upper bounds, and are forward constraints. We may assume that all corresponding arc weights are non-negative (since otherwise the system would be infeasible).
- The difference constraints in (16) arise from lower bounds, and are forward constraints. Again, we assume that all corresponding arc weights are non-negative (as otherwise the system would be infeasible).

Summarizing, all forward arcs have non-negative weights, and with a single exception all backward arcs have weight zero and are of the form $i \to i-1$. The only arc with negative weight is the backward arc from vertex $2n+2$ to vertex 0 in (14). Hence every cycle of negative weight must consist of this arc plus some directed path from vertex 0 to vertex $2n+2$. Recall that the DCS is infeasible, if and only if graph G contains a negative-weight cycle, which is true if and only if the shortest path from vertex 0 to vertex $2n+2$ along arcs with non-negative weights has length strictly smaller than K. This observation in combination with fast shortest path algorithms in directed graphs [3] yields a time complexity of $O(n \log n)$.

Our next goal is to establish a connection to interval graphs, which will yield a linear time complexity. With every forward arc $i \to j$ we associate the closed interval $[i, j]$.

Lemma 2 *Among all shortest paths from vertex* 0 *to vertex* $2n+2$ *(that only use arcs with non-negative weights) let* P^* *be a path with the smallest number of forward arcs. For* $k \geq 1$*, let* $i_k \to j_k$ *denote the* k*th forward arc traversed by* P^**. Then for any pair of consecutive forward arcs* $i_k \to j_k$ *and* $i_{k+1} \to j_{k+1}$*, the two associated intervals* $[i_k, j_k]$ *and* $[i_{k+1}, j_{k+1}]$ *have non-empty intersection.*

Proof. Since P^* moves from vertex j_k to vertex i_{k+1} along backward arcs, we get $i_{k+1} \leq j_k$. If the two associated intervals do not intersect, we must have $i_{k+1} < j_{k+1} < i_k < j_k$. But then P^* could simply skip the forward arc $i_k \to j_k$, and move from i_k to i_{k+1} along backwards arcs at zero cost. This would yield another shortest path with a smaller number of traversed forward arcs. □

Lemma 3 *Consider a sequence of forward arcs* $i_k \to j_k$ $(k = 1, \ldots, p)$ *with overall weight* W*, such that the first arc starts in* $i_1 = 0$ *and the last arc ends in* $j_p = 2n + 2$*, and such that for any two consecutive arcs in the sequence the associated intervals have non-empty intersection. Then the directed graph contains a path from vertex* 0 *to vertex* $2n + 2$ *of weight* W*.*

Proof. As intervals $[i_k, j_k]$ and $[i_{k+1}, j_{k+1}]$ intersect, we get $j_k \geq i_{k+1}$. Hence we can move from vertex j_k to vertex i_{k+1} by a sequence of backward arcs. □

Finally we construct a vertex-weighted interval graph G^*. For every forward arc with weight w, the interval graph G^* contains the associated interval with weight w. Furthermore G^* contains the degenerate intervals $[0, 0]$ and $[2n + 2, 2n + 2]$ both of weight 0. Lemmas 2 and 3 imply that the length of the shortest path from 0 to $2n+2$ in the directed graph G (measured in arc weights) equals the length of the shortest path in the interval graph G^* from $[0, 0]$ to $[2n + 2, 2n + 2]$ (measured in interval/vertex weights). Atallah, Chen & Lee [1] show that the length of the shortest path in a vertex-weighted interval graph can be computed in linear time:

Proposition 4 *(Atallah, Chen & Lee [1])*
Given a set of intervals with weights, an ordering of these intervals according to their left endpoints, and an ordering of these intervals according to their right endpoints, the single-source shortest path problem can be solved in linear time. □

The single-source shortest path problem consists in computing the shortest paths from a given source-interval to all other intervals, where the length of a path is the sum of all interval weights along the path.

Since the endpoints of all intervals are intervals in the range 0 to $2n + 2$, it is easy to sort these intervals according to their left or right endpoints in linear time $O(n)$; this can for instance be done by counting sort or by some variant of bucket sort (see Section 8 of Cormen, Leiserson, Rivest & Stein [2]). Altogether this yields the main result of our paper.

Theorem 5 *The feasibility test for the dial-a-ride problem of Hunsaker and Savelsbergh under time window constraints, riding time constraints, and waiting time constraints can be performed in* $O(n)$ *time.* □

7 Final remarks

Up to this point, we only discussed how to decide whether a given instance is feasible. But if an instance is feasible, then we can also explicitly construct a corresponding schedule in $O(n)$ time: We extend the interval graph G^* by adding the $2n + 1$ degenerate intervals

$[i, i]$ with $1 \leq i \leq 2n+1$ to it, where interval $[i, i]$ has weight 0 and corresponds to variable x_i in the difference constraint system DCS.

Then we use Proposition 4 to compute the shortest path lengths y_i from the source interval $[0, 0]$ to all intervals $[i, i]$ in linear time. It is easy to see that setting $x_i := y_i$ yields a feasible solution for the difference constraint system. Finally, by some straightforward backwards calculations we can determine from this the corresponding feasible solutions for the inequality systems in Sections 3 and 4.

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