Integrated Vehicle Routing and Crew Scheduling (IVRCS) in Waste Management
– Part I –

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Abstract. Planning Waste Management involves the two major resources collection-vehicles and crews. The overall goal of our on-going project with two waste management companies is an integrative approach for planning the routes and the crews of the vehicles.
Here we focus on the route generation as modeled in the first two phases of our three-phase optimization approach. We introduce relevant practical requirements and we describe solution methods that yield first promising results for a real-world data set.

Keywords. Vehicle Routing, Crew Scheduling, Waste Management

1 Introduction and Problem Description

In our joint project several partners work together including the Institute of Mathematical Optimization (Technical University Braunschweig), the Chair of Transportation Systems and Logistics (Technical University Dortmund) and two waste management companies in order to model and solve the following crucial challenge in waste management: The collection of waste in a *waste disposal area* within a given time period (*disposal horizon*) by efficient use of the available resources of collection-vehicles and of crews. The overall goal of the project is an integrative approach for planning the routes and the crews of the vehicles.

In the literature, some work is published integrating Vehicle Routing and Crew Scheduling with application to public transport and railways. However, to the best of our knowledge, integrative planning w.r.t. waste collection is not adequately discussed in the literature. In this area previous publications ([1], [2], [3], [4], [5], [6], [7], [8]) mainly focus on route planning.

For a better understanding the practical problem, we clarify some terminology and emphasize relevant practical requirements for route planning. In the morning vehicles and crews start from a single-depot. They collect the waste in some part of the waste disposal area and, whenever the vehicle is fully loaded,

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they return to the depot and unload the collected waste. Such a single circuit from depot to depot is called *route* and all routes done by a single crew at a day are referred to as *daily crew task*.

Of course there are a lot restrictions which have to be considered:

(1) The quantity of waste collected per route has to fit into the vehicle.

(2) There is a time limit for daily crew tasks which is usually a bit less than the shift duration.

(3) The employees gather credit points for the collected bins, the bigger the bins the higher the credit points. Depending on the credit points gathered in a month the employees get extra wages. To avoid unnecessary hard daily crew tasks there is a limit for the total credit points of a daily crew task.

(4) *Minimal degree of connectivity between the routes in a daily crew task*: We require that the street segment with first disposal in a route r_2 is not too far away from the street segment with last disposal in the previous route r_1 in a daily crew task. Suppose this was not the case and for some reason route r_1 had to be finished a bit earlier in reality (maybe that earlier as expected the vehicle is fully loaded). According to the planned routing as given to the crew, they will have to collect the waste of the remaining part of r_1 at the beginning of the next route. However, in that case, after finishing the remaining part of r_1 there is a time-consuming and inefficient drive to the beginning of route r_2, see Figure 1.

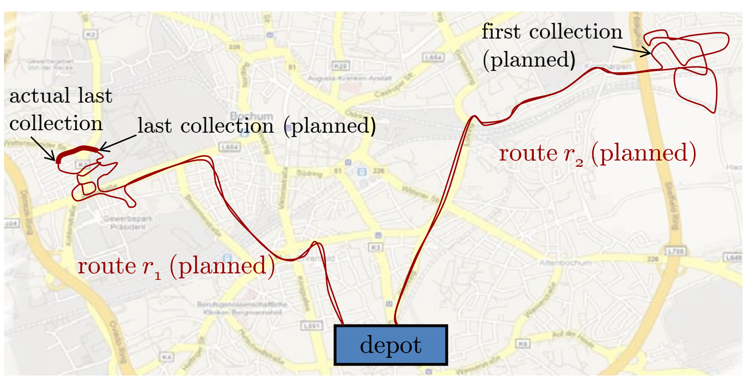

Fig. 1. A planned daily crew task

(5) *Equal time lags between subsequent collections of a bin*: For each bin the *frequency* of collections in the disposal horizon is given, which is a customers request. The common case is a one-time disposal, however, for some bins the customers wish multiple collections in the disposal horizon. The natural

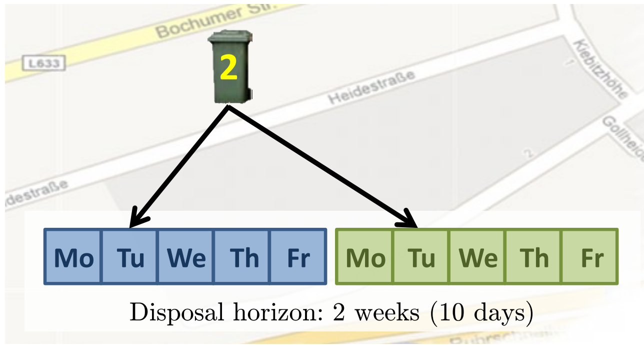

Fig. 2. Equal time lags between subsequent collections of a bin with frequency two

requirement is, that there are equal time lags between subsequent collections of a bin, see Figure 2.

Our practical partners handle the collection of waste on a street segment in the following way: at the m-th collection on a street segment they collect the waste of all bins with frequency greater or equal to m. As a consequence we aggregate the amount of waste on each street segment for each collection. With this aggregation we still can ensure that there are equal time lags between subsequent collections of a bin, since our practical partners do not allow frequency 3 in the current disposal horizon of 10 days.

In both companies the goal with highest priority is

(6) to reduce the number of crews in action.

Since each crew requires a vehicle this goal is equivalent to cutting down the number of vehicles in action. The following two goals relate to robustness of the daily crew tasks:

(7) The maximum duration of a daily crew task is as small as possible. The resulting time buffer is useful in case of any disturbances.
(8) The routes in daily crew task should be closely connected in the previous mentioned way, see restriction 4.

For a description of the requirements and goals from the crew scheduling perspective we refer to the paper of our partners in Dortmund, also contained in this DROPS proceedings.

2 Solution Approach

For the generation of the route plans and the crew schedules we propose the following three-phase approach, where, in Braunschweig, we focus on phases 1 and 2 and where, in Dortmund, our academic partners handle with phase 3.

Phase 1: Generate the daily crew tasks (incl. the routes and the assignment to days) with minimum number of crews required for the disposal process (considering all hard constraints).

Phase 2: Generate the daily crew tasks (incl. routes and assignment to days) w.r.t. minimum number of crews from phase 1 (considering all hard constraints), maintaining ,,good connectivity" between the routes in a daily crew task and minimizing the maximum duration of a daily crew task.

Phase 3: Assign the employees to the daily crew tasks (from phase 2) for all working days over a year, optimizing the goals from the crew scheduling perspective.

Due to the huge complexity of the integrative waste collection problem some decomposition approach seems to be unavoidable. Even the complexity of each of the three phases is quite challenging. However, already phase 1 itself has a certain integrative character: the classical routing is extended by assigning the routes to the daily crew tasks which may be seen as a first necessary step of crew scheduling.

3 Mathematical Models

In the following we present one of our phase 1 models which is a node-based formulation in a directed Shortest-Path-Network $\mathcal{N}(V, E)$ as linear Binary Program.

Basic Data:

Q ... Load capacity of vehicles (maximal amount of waste collectable in a route),

$T_{\max}$ ... Daily working time (maximal time consumption of daily crew tasks),

$C_{\max}$ ... Limit of credit points for a daily crew task,

$\bar{L}$ ... Upper bound for number of required crews,

D ... Number of working days in the disposal horizon.

Data for street segments:

f_s ... Traversal time (without collection) of street segment s (f_s = length of s/average traversal speed),

$\bar{m}_s$ ... Number of collections on street segment s.

Multiple Collections: collection on a street segment ID_i with frequency $\bar{m}_{\text{ID}_i}$ at day d blocks subsequent days in $\bar{D}$ defined as

$$\bar{D}(\bar{m}_{\text{ID}_i}, d) := \left\{ \tilde{d}_j \in (1, \ldots, D, 1, \ldots, D) \mid j \in \{d, d+1, \ldots, d + \left\lfloor \frac{D}{\bar{m}_{\text{ID}_i}} \right\rfloor - 1\} \right\}.$$

Data for nodes $i \in V$ in the Shortest-Path-Network:

· node 0 corresponds to the depot,

· node $i > 0$ corresponds to the m_i-th collection on street segment ID_i with amount of waste q_i, credit points c_i, direction of traversal r_i and service time e_i.

whereas

· $r_i = 1$: fix direction, street segment ID_i is one-way,
· $r_i = 2$: forward direction, $r_i = 3$: backward direction,
· $r_i = 2 \;\Rightarrow\; \text{ID}_i = \text{ID}_{i+1},\; m_i = m_{i+1},\; q_i = q_{i+1},\; c_i = c_{i+1},\; r_{i+1} = 3,$
· $e_i = f_{\text{ID}_i}$ + surplus for collection,
· $1 \leq m_i \leq \bar{m}_{\text{ID}_i}$.

Data for arcs $(i, j) \in E$ in the Shortest-Path-Network:

p_{ij} ... processing time for arc (i, j)
($p_{ij} = e_i + k_{ij}$, whereas k_{ij} is time of shortest path from the end of street segment ID_i to the beginning of street segment ID_j).

Decision Variables:

$$x_{ijld} = \begin{cases} 1, & \text{the } m_i\text{-th collection on street segment ID}_i \text{ directly precedes} \\ & \text{the } m_j\text{-th collection on street segment ID}_j \text{ in daily crew} \\ & \text{task } l \text{ at day } d \\ 0, & \text{otherwise} \end{cases}$$

$$y_l = \begin{cases} 1, & \text{crew } l \text{ operates} \\ 0, & \text{otherwise} \end{cases}$$

For a description of constraints (2)-(6) in the following binary program we refer to Section 1. Constraint (9) ensures the single-time service, constraint (10) is the flow conservation, constraint (11) eliminates subtours and ensures (1), and (12) describes the coupling constraints.

$$
\begin{array}{lll}
(6) & L^* := \min \sum_{l=1}^{\bar{L}} y_l & \\
(9) & \sum_{j \in N(i)} \sum_{l=1}^{\bar{L}} \sum_{d=1}^{D} x_{ijld} = 1 & \forall i \in V : r_i = 1 \\
(9) & \sum_{j \in N(i)} \sum_{l=1}^{\bar{L}} \sum_{d=1}^{D} (x_{ijld} + x_{(i+1)jld}) = 1 & \forall i \in V : r_i = 2 \\
(10) & \sum_{j \in N(i)} x_{ijld} - \sum_{j \in N(i)} x_{jild} = 0 & \forall l, \forall d, \forall i \in V \\
(11) & W_i + q_j - \left(1 - \sum_{l=1}^{\bar{L}} \sum_{d=1}^{D} x_{ijld}\right) \cdot 2Q \leq W_j & \forall i \in V, \forall j \in V \backslash \{0\} \\
(11) & W_i \leq Q & \forall i \in V \backslash \{0\} \\
(11) & W_0 = 0 & \\
(2) & \sum_{(i,j) \in E} p_{ij} \cdot x_{ijld} \leq T_{\max} & \forall l, \forall d \\
(3) & \sum_{(i,j) \in E} c_i \cdot x_{ijld} \leq C_{\max} & \forall l, \forall d \\
(4) & k_{ij} \cdot (\, x_{i0ld} + x_{0jld} - 1 \,) \leq K_{\max} & \forall l, \forall d, \forall i, j \in V \\
(5) & \sum_{j \in N(i_1)} \sum_{l=1}^{\bar{L}} x_{i_1 jld} + & \forall d, \forall i_1, i_2 \in V :\ i_1 \neq i_2, \\
 & \sum_{d_2 \in \bar{D}(\tilde{m}, d)} \sum_{j \in N(i_2)} \sum_{l=1}^{\bar{L}} x_{i_2 jld_2} \leq 1 & \mathrm{ID}_{i_1} = \mathrm{ID}_{i_2}, 1 < \bar{m}_{\mathrm{ID}_{i_1}} = \tilde{m} \\
(12) & y_l - x_{ijld} \geq 0 & \forall l, \forall d, \forall i, j \in V \\
(12) & y_{l-1} \geq y_l & \forall l \\
 & x_{ijld}, y_l \in \{0, 1\} &
\end{array}
$$

The model for phase 2 is just a slight variation of the Binary Program above.

4 Solution Methods and Computational Results

In our real-world data set the street network consists of almost 10,000 street segments, where 2 percent have a forced direction for collection, 60 percent have waste to collect, and 11 percent have multiple collections. Altogether this leads to a bit less than 15,000 nodes in the Shortest-Path-Network. The disposal horizon is 10 days in 2 weeks and the limit for the duration of a daily crew task is 7.5 hours.

Note, it is not possible for standard solvers on ordinary computers to entirely read the Binary Program presented above for our practical instance. Due to the huge complexity it seems hopeless to solve phases 1 and 2 to proven optimality for realistic instances. As a consequence we tested various hierarchical solution approaches for the phases 1 and 2. The solution approach which led to the best practical results so far is the following 4-step procedure.

Step 1: Assign multiple collections to days in the disposal horizon such that there are equal time lags between them.

Step 2: Generate routes (pay attention to the days assigned to multiple collections).

Step 3: Assign the routes to daily crew tasks on particular days in disposal horizon with as few as possible crews.

Step 4: Assign the routes to daily crew tasks on particular days in the disposal horizon with as few as possible crews such that we have ,,good connectivity" between the routes in a daily crew task and such that the maximum duration of a daily crew task is as small as possible.

After step 3 we have a solution for phase 1 and after step 4 we have a solution for phase 2. In steps 1, 3, and 4 we solve Binary Programs with the standard solver CPLEX 12.1. In step 2 we tested various heuristical approaches. A tailored Savings-Method (as known as Clark-Wright-Method) yields the best results up to now. Solving the Binary Program in step 1 is fast, whereas the computational times for solving the Binary Programs in step 3 and 4 vary depending on the choice of the parameters. The tailored Savings-Method in Step 2 takes about 10 hours time and requires almost 12 GB memory.
For random data sets we have an average gap between the optimum and our best lower bound (combinatorial reasoning) of 70 %. For the practical data set the results which we just recently obtained look promising.
As already mentioned this is on-going work. An important next step will be to check together with our practical partners wether the input data we used is realistic enough. Moreover we will try to improve our lower bounds by exploiting other relaxations and formulations; maybe the approach in a recent publication by Letchford and Oukil [9] could be helpful.

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