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Agricultural fleet vehicle routing problem with implements

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1 Introduction

Agriculture is undergoing a technological revolution to meet rising global demand. Autonomous vehicles are integral to modern agricultural practices, yet Agricultural Vehicle Routing Problems primarily address homogeneous fleets with a single type of task and one type of crop. Real-world agriculture, however, involves diverse tractors performing various tasks, such as ploughing, fertilization, fumigation, and harvesting, using attached implements. Coordinating routes for these mixed fleets is crucial for optimizing task execution and resource allocation in contemporary agriculture.

The coordination of two vehicle classes (tractors and implements) simultaneously in agriculture to our knowledge remains unexplored. The concept of movement synchronization, where changes in one route affect others, involves nonautonomous vehicles relying on autonomous vehicles for spatial movement. Such a synchronization is clearly required in agriculture, where an implement is used with a tractor for a time period [1,2]. Various approaches exist in the literature, including one allowing detachment and reattachment during the route, as in the Vehicle Routing Problem with Trailers and Transshipments [3,4]. A different approach, proposed by [5], is to avoid assuming consistent associations between autonomous and non-autonomous vehicles. The Active Passive Vehicle Routing Problem introduces a scenario with active and passive vehicles, where the active vehicles, that dis-

place the passive ones, may change, thus contributing to addressing the synchronization challenge in an agricultural setting [6].

2 Problem formulation

In this section, we present the set-partitioning formulation of the Agricultural Fleet Vehicle Routing Problem with Implements (AFVRPI), solved through column generation. Let us consider a fleet comprising both tractors and implements ($\mathcal{F} = \mathcal{V} \cup \mathcal{M}$), covering routes on the transportation network. The transportation network is represented by $(\mathcal{N}, \mathcal{A})$, where nodes in \mathcal{N} consist of four distinct sets: \mathcal{N}_{tasks} for agriculture tasks, \mathcal{N}_{depots} for tractor and implement depots, \mathcal{N}_{detach} for detaching nodes, and \mathcal{N}_{attach} for attaching nodes. Arcs in \mathcal{A} denote spatial and temporal connectivity, with arc distances represented as d_{ij} . The set of transfer arcs, denoted as $(d, a) \in \mathcal{A}_{transfer}$, includes arcs where implements can be detached $d \in \mathcal{N}_{detach}$ /attached $a \in \mathcal{N}_{attach}$ to tractors. Each task has a given demand, service time, and time window.

Based on task-implement and vehicle-implement compatibilities, each vehicle in the fleet $f \in \mathcal{F}$ has a subgraph representation $(\mathcal{N}^f, \mathcal{A}^f)$ indicating the nodes and arcs it can visit. Routes for tractors and implements are elementary paths within their respective subgraphs. The route-based formulation incorporates binary variables δ_p^v for feasible tractor routes $p \in \Omega^v$ and λ_q^m for feasible implement routes $q \in \Theta^m$. The cost of a route for a tractor v is denoted as c_p^v , and for an implement m , it is denoted as c_q^m . Positive integers a_{ijp}^v represent the number of times arc $(i, j) \in \mathcal{A}^v$ is traversed by tractor v on route p , while b_{ijq}^m represents the same for implement m on route q . Moreover, T_{ip}^v is the time spent at node i if the node is visited with the vehicle v in the path p .

The goal of the AFVRPI is to find a set of feasible routes for tractors and implements that visit all the tasks minimizing the overall cost and respecting the movement constraints. An implement route $q_m, m \in \mathcal{M}$ can be part of the solution if each arc $(i, j) \in \mathcal{A}^m$ corresponds to a compatible tractor travelling the same arc, except for transfer arcs. The restricted master formulation is for the AFVRPI is the following. The objective function (1) is to minimize the total cost of all selected routes. The assignment constraints (2) and (3) are the one-on-one vehicle-implement-task assignment constraints. The arc-coordination constraints (4) require that if an implement travels an arc, it must be coupled to a vehicle. The transfer constraints (5) set the minimum transfer time from an implement to τ . The vehicle and implement constraints (6) impose the assignment of one route to

each tractor and implement.

$$\min \sum_{v \in \mathcal{V}} \sum_{p \in \Omega^v} c_p^v \delta_p^v + \sum_{m \in \mathcal{M}} \sum_{q \in \Theta^m} c_q^m \lambda_q^m \quad (1)$$

$$\text{s. t. } \sum_{v \in \mathcal{V}} \sum_{p \in \Omega^v} a_{jp}^v \delta_p^v \leq 1 \quad \forall j \in \mathcal{N} \quad (2)$$

$$\sum_{m \in \mathcal{M}} \sum_{q \in \Theta^m} b_{kq}^m \lambda_q^m = 1 \quad \forall k \in \mathcal{N}_{tasks} \quad (3)$$

$$\sum_{q \in \Theta^m} b_{ijq}^m \lambda_q^m \leq \sum_{v \in \mathcal{V}} \sum_{p \in \Omega^v} a_{ijp}^v \delta_p^v \quad \forall m \in \mathcal{M}, \forall (i, j) \in \mathcal{A}^m \setminus \mathcal{A}_{transfer} \quad (4)$$

$$\sum_{v \in \mathcal{V}} \sum_{p \in \Omega^v} (T_{ap}^v - T_{dp}^v) \delta_p^v \geq \tau \sum_{q \in \Theta^m} b_{adq}^m \lambda_q^m \quad \forall m \in \mathcal{M}, \forall (d, a) \in \mathcal{A}_{transfer}, \quad (5)$$

$$\sum_{p \in \Omega^v} \delta_p^v = 1, \quad \forall v \in \mathcal{V}, \quad \sum_{q \in \Theta^m} \lambda_q^m = 1 \quad \forall m \in \mathcal{M}, \quad (6)$$

$$\delta_p^v \in \{0, 1\}, \quad \forall v \in \mathcal{V}, \forall p \in \Omega^v, \quad \lambda_q^m \in \{0, 1\}, \quad \forall m \in \mathcal{M}, \forall q \in \Theta^m. \quad (7)$$

3 A column generation approach

To solve the RPM introduced in Section 2, we develop a column generation heuristic, taking into account the independent subproblems associated with each tractor and implement. Each tractor subproblem is an Elementary Shortest Path Problem with Resource Constraints (ESPPRC) incorporating linear costs [6]. This subproblem considers two resources: the distance, restricted by vehicle autonomy, and the time, constrained by task time windows. Since the linear costs only depend on the transfer arcs, as shown in equation (5), we discretize the time to visit those nodes and arcs, by adding duplicated nodes with fixed time windows. Each tractor $v \in \mathcal{V}$ initiates its route from a given depot $s^v \in \mathcal{N}_{depots}$ and ends at the depot $e^v \in \mathcal{N}_{depots}$ by the end of the planning horizon. The implement subproblems are also ESPPRCs, but they only consider the demand constraints. The demand constraint depends on the implements and the tasks that are compatible with it. Some implements do not have a capacity, such as pruning or ploughing, some have a small capacity and need to be recharged (e.g., implements associated with fertilizer spreading), and some have a large capacity and cannot be recharged. For each type of implements, we use a specific optimized ESPPRC algorithm.

Leveraging the distinctive implementation of the subproblem for each vehicle type, the column generation approach proves highly suitable for solving it in a distributed and asynchronous manner, as outlined in [7], improving the convergence speed. Finally, an upper bound is obtained by solving the integer problem with the columns generated so far.

4 Preliminary computational results

Table 1: Preliminary computational results

Instance			MIP model			Column generation		
$ \mathcal{V} $	$ \mathcal{I} $	$ \mathcal{N}_{tasks} $	UB	LB	t(s)/gap(%)	UB	gap(%)	t(s)
5	5	30	418	401	4.23 %	418	4.23 %	1 s
5	5	30	389	353	10.19 %	392	11.04 %	7 s
5	5	30	383	-	200 s	383	0.00 %	32 s
5	5	40	446	419	6.44 %	487	16.22 %	40 s
5	5	40	412	340	21.17 %	425	25 %	2 s
5	5	40	425	412	3.15 %	449	8.98 %	6 s
5	5	50	492	-	566 s	503	2.23 %	92 s
5	5	50	460	411	11.92 %	484	17.7 %	60 s
5	5	50	436	428	1.86 %	481	12.3 %	64 s
5	10	30	647	-	2831 s	647	0.00 %	27 s
5	10	30	659	-	20 s	659	0.00 %	18 s
5	10	30	580	-	1650 s	582	0.34 %	252 s
5	10	40	705	-	2253 s	705	0.00 %	136 s
5	10	40	653	-	295 s	653	0.00 %	12 s
5	10	40	679	-	409 s	679	0.00 %	90 s
5	10	50	755	-	3027 s	758	0.39 %	262 s
5	10	50	673	664	1.35 %	674	1.5 %	396 s
5	10	50	623	611	1.96 %	630	3.1 %	212 s

Table 1 shows preliminary results obtained by running our asynchronous column generation algorithm on 18 small instances. The instances differ in the distances between tasks and the compatibilities of vehicles, implements and tasks. We compare our results with those obtained by solving a MIP formulation with the commercial solver Gurobi 10.0.2. We report the upper and lower bounds returned by Gurobi after one hour of CPU time, and the upper bound returned by our column generation approach. We also indicate the computational time and the optimality gap for both methods. The optimality gap is computed as $\frac{UB-LB}{LB} \cdot 100$ when the optimal solution is not obtained with the MIP model. Our column generation approach obtains solutions faster for all instances and close to the Gurobi solutions in most instances. However, the efficiency tends to decrease when the number of tasks increases and the number of implements is limited. As a future research direction, we plan to improve the efficiency of our algorithm on large instances to outperform the solution of the MIP with a solver. Last, we aim to analyze how different capacities, time windows and compatibility parameters influence the exchange of vehicles and the quality of solutions.

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