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Multi-vehicle refill scheduling with queueing

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ABSTRACT

We consider the problem of refill scheduling for a team of vehicles or robots that must contend for access to a single physical location for refilling. The objective is to minimise time spent in travelling to/from the refill station, and also time lost to queuing (waiting for access). In this paper, we present principled results for this problem in the context of agricultural operations. We first establish that the problem is NP-hard and prove that the maximum number of vehicles that can usefully work together is bounded. We then focus on the design of practical algorithms and present two solutions. The first is an exact algorithm based on dynamic programming that is suitable for small problem instances. The second is an approximate anytime algorithm based on the branch and bound approach that is suitable for large problem instances with many robots. We present simulated results of our algorithms for three classes of agricultural work that cover a range of operations: spot spraying, broadcast spraying and slurry application. We show that the algorithm is reasonably robust to inaccurate prediction of resource utilisation rate, which is difficult to estimate in cases such as spot application of herbicide for weed control, and validate its performance in simulation using realistic scenarios with up to 30 robots.

1. Introduction

In agricultural operations, timing is crucial; if operations are completed too early, or specifically too late, profitability is reduce due to decreases in crop yield or quality. Timing of operations can be negatively impacted by issues with the required components, such as: agricultural vehicle(s), the input material (seeds, fertilizer, herbicide, etc.), and the driver(s). Late completion of the operation can be caused by too few machines, problems in logistics of input material, and availability of driver/operator. By using robotics, the issue of driver/operator availability can be solved through *autonomous* operation. However, core questions remain concerning the proper number of machines to use and the parameters of these machines, such as operational width. In the case of multiple machines (autonomous or human driven) the logistics of input material also plays an important role with respect to operational efficiency.

Operational efficiency, or more specifically *field efficiency*, is defined in the ASAE D497.7 (2011) standard as the real operational performance of a vehicle compared to its theoretical maximum with the given speed and width, without turns. Field efficiency is less than 100% due to turning, irregularly shaped field plots, and refilling, among other factors. Derived from collected data, the ASAE D497.7 (2011) standard defines 70% (± 10%) field efficiency for fertiliser spreaders and 65% (± 15%) for boom sprayers. These numbers are typically used when selecting the proper size of machine for a specific farm.

In the case of multiple robots or vehicles, an important factor in maintaining high field efficiency is to determine the proper refill timing for each unit. Refilling the container of the vehicle with seeds, fertilisers, herbicide, fungicide, pesticide, manure, slurry, lime or fuel is usually done at the edge of the field area. Refilling, or replenishing, the supply of input materials must be done semi-regularly at refill stations and the refill procedure can require a substantial amount of time. Due to varying shaped fields and the distances that vehicles must travel to the refill station, the order in which vehicles are refilled cannot always be the same. Otherwise, the quickest vehicle with the shortest routes has to wait until the others have refilled. Harvesting operations where tanks are emptied at the edge of the field or at a central storage location are analogous to refilling, but for simplicity, in this work we focus our

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discussion on refilling. If multiple vehicles work simultaneously, a given vehicle may need to wait its turn, or *queue*, at the refill station.

We are interested in understanding the optimisation problem that arises in these scenarios: at what points in time should a vehicle pause its work and travel to a refill station such that total refill time (travel, queuing, and refilling) is minimised? We refer to this optimisation problem as *refill scheduling with queuing*.

The refill scheduling problem is relevant to both traditional and robotic agricultural operations. In traditional broadacre agriculture, for example, broadcast spray rig operators typically employ a *greedy* decision strategy where they wait until the spray tank is empty and then drive to the refill station. This strategy, unfortunately, can lead to surprisingly large time losses. Agricultural robots are subject to similar, or worse, time losses (Richards et al., 2015). These losses are exacerbated in small, relatively slow-moving robot systems operating in large areas; a single round-trip to a refill station can require several hours of travel time, as we show through experiments in Section 6. It is critically important to develop a principled theoretical understanding of this problem in order to design efficient algorithms that will support current and future applications of agricultural robots, and increase efficiency in traditional operations.

Interestingly, there has been surprisingly little work that addresses refill scheduling with queuing. Oksanen and Visala (2009) proposed an efficient greedy algorithm that addresses travel time, but not queuing. Bochtis and Sorensen (2009) formulated a variety of related problems under the umbrella of the vehicle routing problem, which is NP-hard, but did not provide a rigorous complexity analysis. The existence of polynomial-time algorithms for certain variants (Oksanen and Visala, 2009; Patten et al., 2016) contradicts the assumption that all variants that can be formulated as vehicle routing problems are NP-hard, and thus motivates the need for a more rigorous approach.

In this paper, we present analysis and algorithms for refill scheduling with queuing. We show that, although polynomial-time algorithms exist for the case of instantaneous refill time, the general problem with non-zero refill time is NP-hard. We also show that the ratio of working time to refill time imposes a limit on the number of vehicles that can work together productively given a single refill station. Based on this analysis, we present two algorithms. The first is an exact algorithms that computes an optimal refill schedule, but is infeasible in practice for all but the smallest problem instances. The second algorithm computes an approximately optimal solution and is effective in practice. The algorithm maintains upper and lower bounds on the optimal solution, and tightens these bounds iteratively. Thus, the algorithm produces higher quality solutions given more computation time, but can produce a valid solution at any time. An algorithm with this property is known as an *anytime* algorithm.

We report simulation results, using examples of spot spraying, broadcast spraying and slurry spreading robots, that characterise the practical performance of our solution in comparison to the greedy approach. Our results show that the performance gap between methods, measured in terms of total time attributed to refilling, can be wide. Importantly, we also analyse the sensitivity of our solution to variations in the actual rate of resource consumption versus the estimated rate. This analysis shows that our algorithm exhibits reasonable performance, particularly in the case where the usage rate is overestimated, and motivates further work in developing methods that directly consider uncertainty in the consumption rate estimate.

The contributions of this work are to provide the first complexity analysis of the refill scheduling with queuing problem, and to present exact and approximate solutions. Our algorithms support the design of software tools that apply to any agricultural robot system that consumes and refills physical resources, and similarly to manually operated agricultural vehicles.

Throughout the paper, we use the term *robot* to loosely imply either an autonomous or human-operated vehicle. We use the term *field plot* to mean an agricultural area where crops are grown.

2. Related work

The work most closely related to ours is by Oksanen and Visala (2009), who propose a greedy algorithm for refill scheduling to reduce time lost in travelling to and from a refill station. The robot monitors its resource level and greedily chooses when to refill. In our previous work, we give an optimal polynomial-time algorithm for this case (Patten et al., 2016). Neither paper, however, considers queuing.

A series of papers has explored the idea of modelling a wide range of optimisation problems in agricultural field operations as instances of the general vehicle routing problem (VRP) (Bochtis and Sorensen, 2009; Bochtis and Sorensen, 2010; Jensen et al., 2015a,b). This work is important for multiple reasons; it focuses attention on the benefits of addressing the computational problems inherent in field operations, and provides a pathway to the convenient use of off-the-shelf solvers. However, there are two severe limitations of this approach. First, the VRP cannot express all possible computational problems of interest to field operations. The problem we study in this paper is one such instance. Second, formulating a problem as an instance of a VRP does not theoretically imply that the problem is as computationally difficult as the VRP. Our previous work (Patten et al., 2016) provides a concrete example of a variant that can be solved in polynomial-time, but also can be (undesirably) formulated as a VRP.

The branch and bound approach is one method that can be used to solve VRPs (Toth and Vigo, 2002) and a wide range of other problems such as information gathering (Best and Fitch, 2016; Binney and Sukhatme, 2012). In adopting this approach, it is necessary to compute upper and lower bounds on the cost of the (unknown) optimal solution. We develop specific algorithmic procedures for calculating bounds that both minimise total refill time (including queuing) and also exhibit reasonable run-time performance. Our work also allows for replanning to account for uncertainty in usage rate estimation, as in Edwards et al. (2015), but we show that replanning is not always necessary.

The problem of computing a plan that visits the entire area of a field plot is an instance of *coverage planning*, a well-studied problem in robotics. A recent survey can be found in Galceran and Carreras (2013). Both single- and multi-robot coverage are NP-hard problems (Rekleitis et al., 2008), but reasonable solutions can be computed using simple methods such as the *boustrophedon decomposition* (Choset et al., 2005). Recent work specific to agricultural applications focuses on choosing an optimal track orientation (Oksanen and Visala, 2009; Jin and Tang, 2011; Hameed, 2014). Here, we assume that track orientation is given, and that the output of a coverage planner is also given. These are reasonable assumptions because track orientation is often fixed ahead of time (as in controlled traffic farming), and coverage planning solutions for this case are readily available in the literature.

Our formulation of refill scheduling is related to the problems of fixed-route vehicle refuelling (Suzuki, 2014; Lin et al., 2007) and electric vehicle recharging (Schneider et al., 2014; Bruglieri et al., 2015; Keskin and Catay, 2016). This work does not address queuing, however. Nam and Shell (2015) address resource contention, but in the context of multi-robot task allocation which does not directly apply to refill scheduling.

In our work we assume that a given field plot has been segmented and that the area to be covered by each robot is thus known. Another view of the refilling problem is then as a scheduling problem in which refilling each robot is a task that must be scheduled periodically (i.e., the span of time in which a robot does not refill has a hard upper bound). At any point on the path of a robot, there exists a fixed cost to schedule the task that is simply the travel distance to the refill station. Then, the goal is to schedule k tasks in a periodic fashion so as to minimise total time spent due to queuing and scheduling costs. This problem bears closest resemblance to *group interval scheduling* (Keil, 1992), in which a set of n independent tasks of possibly differing execution times must be scheduled for execution. This problem is considerably simpler than ours and, due to the queueing costs, even a