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Harvest logistics in agricultural systems with multiple, independent producers and no on-farm storage

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ABSTRACT

The best way to organize the logistics of harvesting agricultural crops requires considering not only the fact that agricultural commodities in general are highly perishable, but also the fact that the organizational structure of the agricultural system in question can vary from crop to crop and from region to region within a single crop. This paper develops a model for planning the movement of the crop from farm to processing plant for crops satisfying two conditions: (1) there are multiple, independent producers (farmers), and (2) no significant on-farm storage exists. We will also briefly describe three different but economically significant agricultural systems in the United States: sugarcane in Louisiana, sugar beets in the northern areas of the United States e.g. South Datoka, Minnesota, Colorado, and vegetable harvesting for human consumption, and will argue that these systems fit the two conditions of our model. We will also briefly explain why several other significant agricultural systems do not fit these two conditions and hence require alternative modeling techniques. Finally, we demonstrate that the model is computationally tractable by introducing new datasets based upon the sugarcane industry in Louisiana. This choice was driven, not only by the fact that the datasets can be constructed entirely using publically available information on the sugarcane infrastructure in Louisiana, but by the fact that this particular organizational structure also appears in both the sugar beet and vegetable processing industries.

1. Introduction

This paper considers a supply chain problem in the agricultural industry that appears in a number of different settings. The problem is that of organizing the logistics of transporting the crop from producers' fields to a single facility at which the crop may be processed for further supply chain distribution or, in the case of sugar beets, stored for future processing at a different location. We consider a class of problems satisfying two conditions: (1) there are multiple, independent producers; and (2) on-farm storage of the harvested crop is impractical or impossible.

The first condition rules out vertically integrated corporations in which the processing facility and the farms are owned by the same entity. This precludes the possibility of allowing a coordinator at the centrally located processing facility to continuously monitor and vary harvesting rates at individual farms as decision variables. While varying harvest rates at individual farms might seem a tad bit far-fetched, it actually arises in the Brazilian sugarcane industry in which vertical integration is the norm and a central controller varies harvesting rates at the fields (fronts) being harvested as conditions warrant. The second condition, that of no on-farm storage, rules out a number of important crops such as corn for which on-farm storage, while not universal, is still quite common with many farms having on-site drying cribs as well as storage cribs in which corn may be stored for years prior to sale or subsequent use. The second condition also implies that the harvested crop is transported from the farm as it is harvested.

This paper addresses a situation in which logistics are planned for a single 24 h period. During this day, the crop is harvested at a set of harvest locations (farms). The crop is moved from the harvest locations to the single facility (for storage or processing) in trucks which then return to the farms to pick up another load. Each harvest location has a pre-specified number of loads that are available to be harvested on the day in question. The locations of the fields being harvested are known as is the location of the single facility to which the crop is being removed. The travel times from each harvest location to and from the single facility are known as are both the time for loading a transport vehicle at the farm and

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the time for unloading the transport vehicle at the facility. We assume that, although the harvest rates at each harvest location are constant, the start times of the harvest at each harvest location are variables that we can set.

The model divides the day into blocks of time which can be of arbitrary length. For each time block, there is a pre-defined unloading target at the single facility. Since the time blocks can be of different length, so can the unloading targets be different from one time block to the next. Actual deliveries of the crop to the facility are, of course, constrained by the availability of resources within the harvesting and transportation system associated with the facility. We take as our objective to minimize the cumulative deviation of actual deliveries to the facility from the desired unloading targets throughout the day.

Note that the unloading target during a time block may be determined by the actual capacity of the facility to process the crop. The objective makes sense in that it spreads the arrivals of crop transport vehicles at the facility to meet the ability of the facility to process those loads. In the event that the processing capacity at the facility remains constant over the day, the objective will attempt to minimize the variance of the arrival stream of transport vehicles at the facility. In the parlance of queueing systems, we will have reduced as far as is possible the variance of the customer arrival stream. Consider that the time spent in queue in a single server queueing system are given by the equation

$$p \times \frac{\frac{\lambda}{\mu}}{1-\frac{\lambda}{\mu}} \times \frac{CV_a^2 + CV_p^2}{2}, \tag{1}$$

where p is the average time required to unload a single crop transport vehicle at the single facility, $\frac{\lambda}{\mu}$ denotes the utilization of the single facility, and values CV_a and CV_p denote the coefficients of variation in the arrival stream and in the processing stream, respectively.

To see why minimizing the variation in the arrival stream makes sense when considering the problem of managing the crop harvest and transport system, note that other parameters in Eq. (1) are properties of the facility and hence lie outside the realm of the crop transport system. Our stated objective is aimed at reducing the coefficient of variability of the arrival stream and, ceteris paribus, the average time that vehicles spend queueing at the facility. Reducing time in queue reduces congestion at the facility, thereby making more effective use of available crop transport vehicles. In the case of the sugar industry discussed in Section 2, it also will shorten the time between harvest and pre-cooling (for sugar beets) or the time between harvest and crushing (for sugarcane) thereby reducing sugar losses. In the case of the vegetable industry, reducing the harvest to process time is also of considerable importance since otherwise the quality of the resulting produce is significantly lessened.

This paper makes several contributions to the literature. First, the paper introduces a tractable two-phase solution approach that overcomes computational challenges seen in analogous problems in the literature. Second, the paper introduces a novel use of a technique from the piecewise linearization of functions to linearize discrete time blocks. The paper also introduces a provably optimal algorithm for determining the number of trucks needed to serve the harvested loads. Finally, our computational results demonstrate not only the computational effectiveness of our approach, but also that spreading the arrival of vehicles as evenly as possible at the mill reduces the number of trucks needed to serve the harvest.

In what follows, Section 2 describes three areas of agriculture in which our model and solution approach is relevant. Section 3 presents a literature review. Section 4 describes our solution approach and presents a formalization of the model that we have presented verbally in the introduction. Section 5 introduces a set of test instances and presents the results of experiments that demonstrate the effectiveness of our approach. The set of test problems are derived from publicly available data on the geographical locations of each of Louisiana's 456 sugarcane farms and 11 sugarcane mills as well as their production and processing rates. These instances allow us to demonstrate the ability of our method to solve realistically sized problems. Section 6 concludes the paper.

2. Application areas

In this section of the paper, we describe three examples of agricultural harvesting and transportation systems that fall into the class of problems covered by the model and presented solution approach. The examples are: (a) sugar beet crops, (b) sugar cane crops, and (c) vegetable crops. We restrict discussion to agricultural systems as they are organized and practiced within the United States. Significant variations exist among countries even for the same crop due to differing factors including ownership structures, climactic conditions, operational scales, and technological infrastructure. Doubtless, there are additional examples in other countries as well as in the United States that satisfy the conditions of the model, but our purpose here is not to develop a comprehensive catalog of agricultural supply chain problems that fit into this framework, but rather to show that this framework has nontrivial applications. Three significant examples within United States agriculture seem sufficient for this purpose.

2.1. Sugar beet crops

Sugar beets are an economically significant crop in the United States. In 2014, 1,147,000 acres were harvested, yielding approximately 4.88 million tons of sugar (United States Department of Agriculture Economic Research Service, 2015a). Estimating the economic value of this crop by the average world raw sugar price of 16.34 cents per pound (United States Department of Agriculture Economic Research Service, 2015a), which is less than the prevailing US price due to governmental price supports during the year in question, we get an estimated economic value for the crop of approximately $1.595 billion. The calculated value would, of course, be higher had we used the actual prevailing price in the U.S., but doing so would overstate the true economic value of the crop due to the government price supports.

In the United States, sugar beets are grown primarily in the northern plains states because the weather conditions are favorable. It is typical for sugar beet farmers to belong to a coop that owns one or more factories that process sugar beets into sugar and associated by-products. The Southern Minnesota Sugar Beet Cooperative, for example, has 500 growers and operates 12 receiving stations as well as one factory for processing the sugar beets (Souther Minnesota Beet Sugar Cooperative, 2015). The Western Sugar Cooperative, as another example, has over 1000 growers and operates 43 receiving stations, 7 storage locations, and 5 processing plants (Western Sugar Cooperative, 2015).

Sugar beets reach their peak sugar content in early October and begin to lose sugar thereafter until, if harvesting is delayed until January, they may have lost up to 85% of their initial sugar content. Furthermore, sugar beets deteriorate immediately after harvest, and the sugar loss varies directly with the temperature at which the sugar beets are stored (Investment Centre Division of the Food & Agriculture of the United Nations, 2009).

These facts seem to drive much of the protocol followed in the United States for harvesting and processing sugar beets. In the United States, the sugar beet harvest begins with a small pre-pile harvest in September that allows growers to open up roadways