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Research paper

A corn-stover harvest scheduling problem arising in cellulosic ethanol production

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ABSTRACT

In this paper, we address a corn-stover harvest scheduling problem (CSHSP) that arises when a cellulosic ethanol plant contracts with farmers to harvest corn stover after the grain harvest has been completed. The plant contracts a fleet of harvesting crews, which must be assigned by the plant scheduler to harvest fields as they are called in by the farmers over the harvest season. First, we study the static CSHSP, in which the call in times for the fields are assumed known at the beginning of the season, and propose a mathematical programming-based approach that we show to generate solutions with an average optimality gap of only 6.1% for real-life-inspired instances. We also consider the dynamic CSHSP, in which the call in times are not known at the beginning of the harvest season and the requests arrive randomly over time. The method that we develop for the solution of this problem incurs costs that are about 4.8% higher, on average, than those incurred for the static case. These results exhibit the proposed approach to be robust for use by a plant scheduler in his/her efforts to optimize harvest scheduling as the actual season unfolds. Our proposed approach can also effectively deal with uncertainties encountered in a commercial harvest.

1. Introduction

Cellulosic ethanol, produced from agricultural residues (e.g, straw or corn stover) or energy crops (e.g, miscanthus or switchgrass), can be used as a substitute for the petroleum-based fuel used in the transportation sector. It also causes lesser greenhouse gas emissions as compared with the petroleum-based fuel. The Energy Independence and Security Act (EISA) of 2007 established a minimum volume of renewable fuels required for blending with fossil fuel, to increase from 9 billion gallons in 2008 to 36 billions gallons by 2022. By that year, 44.4% of the 36 billion gallons of renewable fuel must be produced from cellulosic ethanol in the U.S. in order to achieve the desired reduction in greenhouse gas emissions from the transportation sector.

Corn stover, the residue or the remainder of the plant left after harvesting corn, has been identified as a feedstock for the production of cellulosic ethanol [1]. Corn is the largest U.S. crop in terms of total production, and corn stover is the biomass used for two cellulosic ethanol plants that are in the process of being commissioned. These are the Poet plant located in Emmetsburg, Iowa [2], which is expected to ultimately use 258,500 dry megagrams (Mg) of corn stover per year, and the DuPont plant located in Nevada, Iowa [3], which is expected to use 340,000 dry Mg of corn stover per year. Therefore, it is important to develop a methodology to effectively manage corn-stover harvesting and make cellulosic ethanol economically competitive with fossil fuels.

Corn-stover harvesting takes place only after the grain harvesting has been completed; and, once harvested, the farmers want the stover to be removed as quickly as possible so that they can proceed with the fall operations needed to prepare for the spring planting. Both the POET-DSM and DuPont facilities employ several companies to perform corn-stover harvesting, and each of these companies may provide several harvest crews. These crews will hereafter be referred to as balers. Each crew has the set of equipment needed to collect, bale, and transport the stover to a storage location, typically refereed to in Midwest supply systems as

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"roadside storage." At a later time, this baled stover is loaded onto trucks for transport to the cellulosic ethanol plant. This system eliminates the need for corn producers to own and maintain expensive stover harvesting equipment that they will use only for a five-week harvest season. The centralized management of the harvest requires the scheduler employed by cellulosic ethanol producer to coordinate and assign the balers to fields as they are "called in"-where a producer calls the ethanol plant to inform them about readiness of a field for harvesting, and then, the scheduler at the plant directs the balers. This study focuses on developing cost-effective schedules for the balers that can be used in practice by the plant.

It facilitates discussion to simply identify an equipment set as a "baler", and to refer to the cellulosic plant as a "depot". Note that we use the terms base, depot and plant interchangeably. Fig. 1 represents features of a dynamic CSHSP in which a unique baler is located at the central depot denoted by 1 (square), and three Fields (2, 3, and 4, denoted by circles) are ready to be harvested at time zero. The number of days required to harvest Fields 2, 3, and 4 are one, two, and one, respectively, calculated for each field by considering a unique baler as follows: field area (hectares) × expected corn stover yield (Mg/hectare) divided by the baler capacity (Mg/day). Furthermore, each field has a time window, $W_f = [R_f, D_f]$, that specifies the time period during which it should be harvested, where R_f is the ready time (call-in time) of Field f and D_f its due date. In this example, we have $W_2 = [1,5]$, $W_3 = [1,7]$, and $W_4 = [1,6]$, where both R_f and D_f are known at time zero, $R_f = 1$ since all fields are assumed to be ready for harvesting on the first day, and D_f depends upon the field. The goal is to determine a route for a baler that minimizes the total routing cost and the due-date-related-penalties for late harvest. The optimal schedule for Day 1 (period 1), shown in Fig. 1 (a), is $1^{(0)} - 2^{(1)} - 3^{(2)} - 3^{(3)} - 4^{(4)} - 1^{(5)}$, where $f^{(t)}$ denotes that Field f is harvested during Period t. At the end of Day 1, two new fields, denoted by 5 and 6, called-in to the plant with their required number of harvest days given by one day each, and their time windows given by $W_5 = [2,8]$ and $W_6 = [2,8]$, where both R_f and D_f are known at the end of Day 1 and $R_f = 2$ since these fields are ready for harvesting on Day 2. Given this information and the fact that Field 2 has already been harvested and that the baler is located in this field, the problem is reoptimized in view of the availability of Fields 5 and 6. The new route generated is $1^{(0)} - 2^{(1)} - 5^{(2)} - 6^{(3)} - 3^{(4)} - 3^{(5)} - 4^{(6)} - 1^{(7)}$ and it is shown in Fig. 1 (b). Note that, now, the baler first visits the new arrivals (which might not always be the case), Fields 5 and 6, and then it continues with its original route (Fields 3 and 4). In general, multiple balers of each technology may be available, and a given field can be visited by multiple balers of the same technology at the same time. These technologies pertain to formation of rectangular bales (1 $m \times 1.22$ $m \times 2.44$ m), and round bales (1.83 m diameter × 1.52 m long). Note that, technically speaking, the geometries of these two types of bales are actually cuboids and cylinders, respectively; nevertheless, we use the more vernacular terms for convenience. The capacities of these balers can be different and we incorporate this feature in our analysis.

The contributions of this paper are as follows. First, we introduce a new and practical problem that is key for successful operation of cellulosic ethanol production facilities that are expected to grow in number. Second, we propose a mixed-integer programming formulation to model the CSHSP and develop both effective and practical approaches to solve the static and dynamic CSHSPs. Finally, we generate several insights for use by a "scheduler" at a bio-fuel plant in his/her efforts to coordinate harvesting operations.

This paper is organized as follows: In Section 2, we present the harvesting system under study and provide a brief literature review of related problems. In Section 3, we propose a mixed-integer programming formulation for the static CSHSP; and, in Section 4, we propose an effective approach to generate an advanced-start solution to obtain near-optimal solutions to this problem. In Section 5, we present a periodic re-optimization scheme to solve the dynamic CSHSP. Computational results on the application of this methodology to a real-life dataset and results of a sensitivity analysis are presented in Section 6. Finally, concluding remarks are made in Section 7.

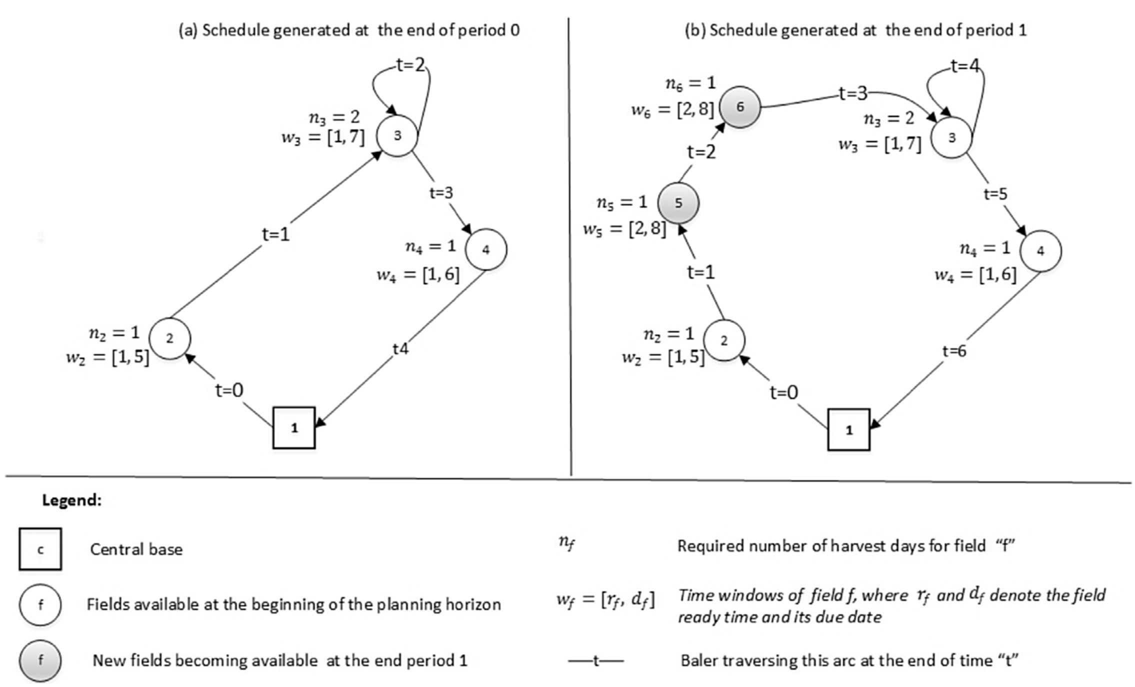

Fig. 1. Features of the corn-stover harvest scheduling problem (CSHSP).