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Modelling corn silage harvest logistics for a cost optimization approach

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ABSTRACT

Harvesting corn silage requires balancing the capacities for harvest, transport, and storage operations to eliminate bottlenecks.

The overall goal of this paper is to simulate the silage harvest system in order to provide the technicians with a decision support tool. This tool will be useful when performing both the strategic planning at the beginning of the harvest season, and in daily decision making, in order to determine the right combination of resources according to fields to harvest. A model was constructed to evaluate the handling system comprising the harvest, transport and packing of forage intended for corn silage.

In order to provide a real example of the usefulness for strategic planning by the tool developed, the harvesting of 590 fields of corn silage in a region of NW Spain was simulated. The model obtained provided a value of 27 trucks to obtain lower harvesting costs if 6-row SPFH were used and 33 trucks with 8-row SPFH. The proper packer capacity at the silo was 3.35 t min^{-1}. The impact that the matching of equipment has on the costs and on the length of the harvest season for each of the harvesters analyzed was more significant with 8-row SPFH. If the number of trucks is less than 30, a 6-row SPFH is more cost efficient than an 8-row SPFH. On the other hand if the number is greater, then the use of the 8-row SPFH would incur lower costs. The harvesting process is more sensitive to changes in the packing capacity than to the number of trucks used relative to the optimum value determined.

1. Introduction

In the harvesting process of corn silage, once the proper maturity and moisture content has been reached, the primary management concerns are to harvest the crop as quickly as possible, avoid runoff and store and treat the corn silage in a manner that eliminates and excludes as much oxygen as possible. These steps will ensure a fast and efficient fermentation with minimum losses during ensiling, storage and feed-out. Research at the USDA Forage Research Center supports mechanical processing in corn silage management as it improves feed efficiency and milk production (Shinners et al., 2007). However, the equipment is expensive and may not be economically viable in smaller operations. Small farms are not able to capitalize on new technology because of the high cost of purchasing large equipment. Consequently, in recent years, in milk producing areas of Western Europe, forage processing plants have been created and operate cooperatively. With this procedure, farmers transfer their field forage (corn silage) to a forage processing plant that manages the corn silage process (including harvesting and storing).

The logistic process includes multiple harvest, transport, and storage operations. The harvest operation involves self-propelled forage harvesters (SPFH), trucks for transport, and machinery for silage packing. All of these need to be co-ordinated, and the number of equipment components needs to be adjusted according to the field's capacity – all under a tight schedule, with a large number of fields to harvest. Bottlenecks within transport or unloading operations can reduce the capacity of harvest operations (Buckmaster, 2006). For this reason, many researchers have used simulation models to analyze and optimize these complex systems. Several authors have successfully applied these models to commodities (Berruto and Busato, 2008; De Toro et al., 2012; Higgins and Davies, 2005; Ravula et al., 2008). The simulation demonstrated the usefulness of systems analysis in predicting the amount and cost of biomass supply in appropriate resource allocation to minimize bottlenecks.

The overall goal of this paper is to simulate the silage harvest system in order to provide a decision support tool for technicians that manage this process. This tool will be useful when performing both the strategic planning at the beginning of the harvest season and the daily decision making, in order to determine the suitable

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combination of resources according to the fields to harvest. The specific objectives of this paper are:

- To develop a model to quantify resource allocations for biomass supply and transport operations.
- To provide an example of the usefulness of the decision support tool for strategic planning:
  - Comparing the performance of the system with different SPFH header widths.
  - Evaluating different resource combinations, in order to minimize the total system costs.
  - Determining which elements have a greater impact on the behaviour of the system via a sensitivity analysis.

2. Materials and method

2.1. Description of the corn silage process

In northern Spain corn silage is usually harvested with SPFHs. This process involves SPFHs and dump trucks for transport to bunker silos at the forage processing plant, which may be several kilometres from where the corn was harvested. The cycle includes three parallel machinery operations: harvesting, transporting and packing at the silo. SPFH travel between farms should also be considered.

The extended use of SPFHs, with a hopper for on-board storage, has been encouraged in recent years in our latitudes due to small, irregularly shaped fields. Forage is unloaded into dump trucks when the hopper is full. To do this, the hopper needs to be held over the truck. The loading capacity of the trucks is equivalent to, or slightly larger than, the capacity of the on-board storage of the SPFH. Tractors and loading shovels carry out the packing at the silo.

Typically, farmers estimate when corn forage has reached the suitable moisture content to be harvested, subsequently notifying the processing plant and request its harvest. The processing plant schedules the overall silage process (harvest, transport and packing) for each week. All partners' requests are harvested on a first-in, first-out (FIFO) basis. A farmer's entire fields have to be harvested before starting on the next farmer's fields. This is because farmers want all their fields to be harvested consecutively. Fields are assigned to SPFH by a proximity criteria (SPFH have a reduced travel speed), and trucks are assigned trying to minimize SPFH waiting times.

An average corn silage harvest season in northwest Spain ranges from 35 to 40 days, typically from 20th September to 30th October. Before the start of the harvesting season, the technician that manages the harvest should perform a preliminary scheduling. Their objective is to estimate the combination of resources needed to harvest the fields in the available time with minimum cost. Obviously this schedule must be checked daily according to the weather and crop conditions. Nonetheless, the changes in planning generally involve varying the workday, while trying to keep the harvesting resources as constant as possible. This case study was conducted at a forage processing plant (CAVI) located in Ribadeo, Galicia (Spain). The harvesting process of corn silage during the 2011 harvest season was simulated. Four SPFH of the same brand and model (New Holland FX58 with a Racine 2025 bunker) were considered. The allocation of SPFHs to the fields, the order of harvesting and the original routes were maintained, because our objective was to predict the performance of the system using different resource allocations and not route management. Table 1 reflects the fields harvested by the four SPFH considered.

The fields for harvesting are found at a maximum distance of 30 km from the CAVI, the majority of which are being situated being 1 and 10 km away. Fig. 1 shows the spatial distribution of these fields.

Table 1
Number of fields and farmers involved.

	Fields	Farmers	Area (ha)	Harvest season (days)
SPFH1	181	27	215.5	33
SPFH2	161	38	221.2	37
SPFH3	158	45	265.3	40
SPFH4	90	22	128.3	23

2.2. Modelling of the corn silage harvest system

The development of the process model has been carried out primarily to reflect the reality of working conditions.

2.2.1. Harvester performance

The throughput (material capacity) of the forage harvester was obtained by the expression (1), according to ASABE EP 496.3 (ASABE Standards, 2011).

$$\mathrm{Cm} = \mathrm{Ca} * Y \qquad (1)$$

where

Cm, throughput ($\mathrm{t\,h^{-1}}$).
Ca, effective field capacity ($\mathrm{ha\,h^{-1}}$).
Y, crop yield ($\mathrm{t\,ha^{-1}}$).

Data for the harvester activity during the 2011 corn silage harvesting season were recorded by means of a telemetric system (Amiama et al., 2008). The SPFH considered can be equipped with different headers, with 8 rows which have a 6.0 m working width, or 6 rows which have a 4.5 m working width.

When a SPFH ends its activity in a field it moves to the next field to harvest. Travelling times between fields have been registered.

Table 2 shows the values used to simulate the harvesting system.

2.2.2. Truck cycle

The cycle time for the transport without idle time, *CTt* ($\mathrm{h\,cycle^{-1}}$), was obtained from the time between two successive unloading operations for each of the transports in the cycle, according to the expression (2).

$$CTt = Ttu,a + Tt + Tht,t \qquad (2)$$

where

Ttu,a: Alignment and unloading time for the truck at the silo, ($\mathrm{h\,unload^{-1}}$). This time comprises the period from arrival of the transport at the silo until the transport finishes unloading and starts to make its way back to the field. An average value of 0.074 h was obtained from 30 unloading times.
Tht,t: Time for harvest/transport interaction and transfer, ($\mathrm{h\,unload^{-1}}$). This time comprises operations for unloading forage into the transport vehicle. The value of *Tht,t* (comprised in the effective field capacity of the harvester) was determined recording 156 unloads, with an average value of 0.033 h being obtained.
Tt: Transport travel time (h). Time required for round trip (field-silo-field).

The loading capacity of the trucks is equivalent to, or slightly larger than, the capacity of the on-board storage of the SPFH. In order to determine the travel speed of the transporter, GPS data loggers were attached to the trucks, and signals were analyzed. A