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Simulation model for the sequential in-field machinery operations in a potato production system

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A B S T R A C T

In potato production multiple sequential operations have to be carried out during the yearly production, and each operation may have its own set of operational features, given by the used machinery. An optimal planning for one operation may lead to restrictions and reduced efficiency to later operations. Therefore, there is a need to develop an approach for predicting and optimizing the overall performance of all operations, given a selected field and the required machines. The work processes with corresponding sequential decisions of each operation involved in the potato production were described by using IDEF modelling approach and implemented using the MATLAB® programming software. Experiments for all the relevant operations in potato farming (bed forming, stone separation, planting, spraying and harvesting) were carried out and monitored in four experimental fields to quantify the set of input parameters and to validate the simulation model. The simulation model predicted the field efficiency (the ratio of the time a machine is effectively working to the total time committed to the whole operation) and the field capacity (the area processed per unit of time) with satisfactory precision for all operations in all fields. The errors in prediction of the field efficiency and the field capacity ranged from 0.46% to 4.84% and from 0.72% to 6.06%, respectively. In addition, the capability of using the developed model as a management-planning tool for decision support on operational decisions (e.g. driving direction, reloading position) and machinery dimensioning (e.g. tank/hopper size) was demonstrated.

1. Introduction

Most arable crops are annual and the cultivation requires the successful and well-timed execution of a sequence of field operations, beginning with the soil preparation and sowing and ending with the harvest. Each field operation requires specific machines, and often the machines are even specific for the crop. It is in the interest of the farm manager to optimize the efficiency of the machines, such that the field operation is executed with sufficient quality at the lowest possible cost. The cost of execution of a field operation may include several factors, such as the operators' salaries, the depreciation of the machines, the consumption of fuel and input material (seed, fertilizer, etc.), the damage to the soil (soil compaction) and the crop (damaged plants, spilled harvested material, etc.). The efficiency of each field operation is determined by a range of selected operational feature (e.g. driving direction, working width, working speed, track sequence, turn type, etc.).

Farmers strive to optimize the execution of the field operations by applying their acquired knowledge and experience. However, an experience-based plan might lead to sub-optimal planning due to the complexity of this type of decision making process that involve competitive criteria. Instead of acquiring experience in practice, simulation models have proven to be valuable tools for farm managers providing a basis for making managerial or technical decisions by being able to simulate the consequences of a great number of alternative scenarios in a more time and cost effective manner. In the last few decades, a considerable number of field operation simulation models have been developed and applied to analyze and optimize the production process and reduce the cost in agricultural field operations. These simulation models include models of grain harvesting (Benson et al., 2002; Busato, 2015; de Toro et al., 2012), plantation in greenhouse (Bechar et al., 2007; van 't Ooster et al., 2012, 2014), manure handling (Bochtis et al., 2009; Busato et al., 2013; Hameed et al., 2012) and tillage (Sørensen and Nielsen, 2005). However, a common characteristic of the above-mentioned models is that they are only able to simulate a single field operation.

There is a need for models that can simulate all the required operations of an entire growing season of crop production systems. The reason for this is that the operations are not independent, so the optimal plan for one operation is likely lead to restrictions

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and reduced efficiency for the subsequent operations. Thus, the combination of optimal plans for each operation is not necessarily an optimal plan, not even a feasible plan, when the entire sequence of operations of the growing season is considered. For example, the optimal driving direction may not be the same for all field operations, but for fields with crops cultivated in rows or beds or for fields with Controlled Traffic Farming (CTF) the driving direction cannot be changed from operation to operation. Likewise, for operations using machines with different working widths there is a strong inter-dependency that must be taken into account. The decision-making process in multiple operations planning is very critical in the case where an operational feature should be identical in all operations.

This paper considers a potato production system as case for in-field sequential machinery operations modelling. Potatoes are cultivated in beds, so once the beds are formed the driving direction is determined for the remaining operations of the season. The working widths of the machines vary from the width of a single bed (e.g. planting) to multiple beds (e.g. spraying), which also has influence on the optimal bed layout design of a given field. Potato production includes complex field operations, where multiple cooperating machine units have to be coordinated in order to achieve optimization of the performance of the overall system. For instance in planting, coordination may encompass the determination of locations of the refilling units (small mobile containers with seed potatoes) and of the appropriate refilling quantity for the planter in order to apply the next round of planting based on the application rate. However, it is quite complex for the farm manager and machine operators to make these decisions and coordination appropriately.

The objective of this paper was to develop a simulation model for multiple sequential operations in a potato production and to demonstrate the capabilities of this model as a decision support system for operations management. The detailed description of these operations is presented in Section 2.1, the work process in each operation is analyzed and modelled in Section 2.2 and the model is implemented in Section 2.3. Section 3 explains how experimental operations in four fields were conducted to quantify input parameters and validate the simulation model. Next, in Section 4 it is demonstrated that the validated model is feasible to provide support of field operational decisions such as driving direction, fieldwork pattern, etc. Finally, conclusions are made in Section 5.

2. Development of the simulation model

2.1. Description of the potato production system

In potato production, five sequential field operations are executed each growing season: Bed formation, stone separation, planting, spraying and harvesting.

(1) Bed formation: This is a crucial step that determines the potato bed layout and wheel tracks for all subsequent field operations of the entire season (Fig. 1a). The bed former uses shaped metal plates to lift up the soil and form it into one or more beds.

(2) Stone separation: This operation is also a part of the seedbed preparation to ensure that the seedbed is free of oversize stones and clods in order to provide ideal growing conditions for the potatoes, as well as to reduce the need for picking up stones and clods and sorting them from the potatoes during harvest. Usually, the operation is completed by using a stone separator which enables the fine soil to fall through sieves into the bed, while the oversize stones and clods are transferred by a conveyor to an adjacent furrow between previously formed beds. The conveyor can be adjusted either to the right or left side when the stone separator is at the end of each bed. In successive operations the machine's tires run on the ridge of the processed stones and clods to bury them between alternate tracks (Fig. 1b).

(3) Planting: Potato planting starts immediately after the stone separation, normally by the use of automated planters. The planter is attached behind a tractor with the seed potatoes stored in a small tank, called the hopper. Special cups lift the seed potatoes from the hopper and place them with accuracy distance into the tracks. The depth of sowing is about 5–10 cm and the distance between potato tubers along the rows are about 20–40 cm (Fig. 1c). Due to capacity constraints the hopper needs to be refilled from the reloading station (Fig. 1d) occasionally. This is done by driving to the headland area where one or more reloading units are located.

(4) Spraying: Spraying with herbicides, pesticides or fungicides are usually performed around 10 times during the growing season (Fig. 1e).

(5) Harvesting: The most common harvest method is using a potato harvester with diggers, depending on the bed type, which can dig out the potatoes from the bed. Soil and crop are transferred onto a series of sieves where the loose soil is sieved out. The potatoes are conveyed to a separation unit at the back part of the harvester. The potatoes then either go on to a side elevator or into transportable storage units that are located in the field or along the field boundary (Fig. 1f).

The above described operations can be categorized into three groups, according to whether material flows into or out of the field: Material neutral operations (MNO) (bed formation, stone separation), material input operations (MIO) (planting, spraying), and material output operation (MOO) (harvesting). The operations of each category have similar work processes, so they are modelled generically in the next section. Furthermore, agricultural machines involved in those operations are classified as primary units (PUs) that perform the main field task (e.g. tractors with implements or self-propelled machines) and service units (SUs) (e.g. a tractor with trailer) that load or unload the PUs during the operation (Bochtis and Sørensen, 2009; Bochtis and Sørensen, 2010).

2.2. Modelling of the work process

The IDEF3 modelling method (Mayer et al., 1995) was chosen to model the work process of tasks and decisions involved in the potato production system. IDEF3 diagrams describe workflows as an ordered sequence of events or activities in a situation or process (Kusiak and Zakarian, 1996). The IDEF family of functional modelling languages has been extensively used in the industrial area for design and manufacturing processes, business systems modeling and project management (Kusiak et al., 1994; Shen et al., 2004). In the past decade IDEF has been applied to describe the work process of various operations in the agricultural context, e.g. in food chain traceability systems (Hu et al., 2013; Thakur and Hurburgh, 2009; Zhang et al., 2011), in harvesting of roses (van 't Ooster et al., 2014), in rice harvesting (Busato, 2015), in biomass supply chain (Zhang et al., 2012) and in information management systems in viticulture (Peres et al., 2011).

An IDEF3 process flow description is made up of units of behaviors (UOBs), links and junction boxes. A UOB represents a process, activity, action or decision occurring in the process. Links represent the relationships between these UOBs, consisting of three types of links: precedence, relational, and object flow links. In this paper, only the precedence links indicating a simple temporal precedence between UOBs were used. Junctions show the logic branching within a process, which include the logical *AND* (&), *OR* (*O*) and