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A flow-shop problem formulation of biomass handling operations scheduling

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ABSTRACT

Currently, the planning of the biomass collection operations is performed relying on the contractor's experience without the use of any dedicated planning tool. It is expected that more explicitly formulated planning tools would provide benefits on securing the supply chain of biomass feedstock. In this study, the problem of finding a permutation schedule for a number of geographically dispersed fields where biomass handling operations have to be carried out involving a number of sequential tasks, was formulated as a flow shop with sequence depended set up times scheduling problems as known in the industrial domain. By applying the approach to a case study involving experimental recording of the operations executions, the execution of an optimal schedule was found to give a reduction of 9.8% in the total time as compared to a schedule based on the tacit knowledge of the operations manager.

1. Introduction

Traditionally, in biomass production systems the developed engineering scheduling approaches deals mainly with the seasonal planning of field operations (e.g. Sørensen, 1999). This type of pure scheduling problems involves assigning labour and machinery recourses to the operations and assigning the operations to periods in time. The first scientific approaches for supporting this decision process in agriculture appeared in early 1980s (e.g. van Elderen, 1980; Fokkens and Puylaert, 1981), mainly based on linear programming methodologies. Wijngaard (1988) implemented and compared three different models for farm operations management namely, a dynamic programming model, a linear programming model, and a simulation model. Recent approaches for a long term cropping schedule involve other methodologies such as stochastic programming (Darby-Dowman et al., 2000), hybrid petri nets (Guan et al., 2008) and metaheuristics (e.g. simulated annealing, and genetic algorithms) (Guan et al., 2009).

The above mentioned scheduling type belongs to the operational planning level of the farm operations management system (Sørensen et al., 2010). Another type of scheduling in biomass production systems that also belongs to the operational planning level is the sequencing of tasks that compete for shared resources. An example of this scheduling type is the planning of large-scale biomass harvesting and handling operations where a series of sequential operations (e.g. cutting, raking, baling, and loading) have to be performed at a number of geographically dispersed fields. This planning task is becoming particularly important as an integral part of the biomass collection for bioenergy production use since securing the supply chain of biomass feedstock will increase the demand for advanced agricultural fleet management tools. In most cases, the planning of the biomass collection operations is performed relying on the contractor's experience without the use of any dedicated planning tool (Sørensen and Bochtis, 2010). Currently, the research efforts within this planning domain are limited. As an example, Basnet et al. (2006) introduced a scheduling method for harvesting of renewable resources based on a Travelling Salesman Problem (TSP) approach combined with greedy and tabu search heuristics. Bochtis and Sørensen (2010) showed that scheduling and planning problems for agricultural field operations can be cast as vehicle routing problems with time windows (VRPTWs) instances and, consequently, it is possible to apply advanced methods developed specifically for the solution of these instances. However, the development of a system that can be implemented to real-life biomass collection planning has to be combined with tools that can precisely predict the time requirements of all tasks involved in the related operations. This is also important in terms of reliability of the biomass supply chain which takes place in a stochastic environment. However, the difficulty in dealing with stochastic measures like availability and reliability concerns the practical implementation of these measures in terms of quantification and task times prediction (Sørensen, 1999).

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In this paper, an industrial engineering approach as regard the problem of scheduling of sequential biomass handling operations is presented. The particular objectives are:

(1) The formulation of the planning problem of multiple-fields sequential operations as a flow shop with set up times as part of the scheduling problem.
(2) The demonstration of the approach implementation using a real-life small scale example.
(3) To assess the impact of the uncertainty in the task times prediction on the applicability of the pursued approach.

2. Problem formulation

The scheduling problem considered in this study involves finding a permutation schedule for a number of geographically dispersed fields where biomass handling operations have to be carried out involving a number of sequential tasks (e.g. cutting, raking, baling, and loading), while this permutation minimises the total completion time of the whole operation (i.e. the execution of all tasks in all fields). As will be seen in the following, this problem will be proven equivalent to the well-known optimisation problem flow shop with sequence dependent set-up times (SDSTs) (Logendran et al., 2006; Zandieh et al., 2006). The general flow shop scheduling problem (Wu et al., 2012; Kalczynski and Kamburowski, 2012; Weng et al., 2012) involves a set of m machines in series (processors) and a set of n jobs where each job comprises a set of m tasks which must be processed on each one of the m machines. All jobs have the same ordering of tasks having to be processed first on machine 1, machine 2, …, and finally, on machine m. In the case of the SDST, each job will have a set-up time assigned which will depend on the immediately preceding job. As an example of the SDST flow shop problem, the printing process can be mentioned, where in an industrial shop floor the cleaning and set-up times of the printing presses depend on the size of paper, and the colour of ink used by the preceding job.

In order to cast the scheduling of biomass handling operations as a SDST flow shop problem, (a) a "job" in the flow shop description will equal a "field" and (b) the "set-up time" in the flow shop description will equal the "inter-field travelling time".

Let $F = \{1,2,3,\ldots\}$ denote the set of fields (indices) where a number of sequential tasks have to be scheduled (the total number of fields is denoted as $|F|$). Let F_0 denote the extended set of fields that includes the machinery depot (denoted by the index 0), $F_0 = F \cup \{0\}$. Let M denote the set of the different machine types or equivalently, the different types of tasks that must be executed. The time required to complete a task is a function of the machine and the field features and consequently, let o_{ij}, $i \in M$, $j \in F$, denote the required time for the task carried out by machine i in field j. Let t_{ijk} denote the travel time of machine $i \in M$ from physical location (field or depot) j to field k; $j \in F_0$, $k \in F$. A set of variables are introduced representing the starting time, s_{ij}, of the task executed by machine $i \in M$ at field $j \in F$. In order to formulate the optimisation problem based on the structure of the travelling salesman problem, the binary decision variable x_{jk}, j, $k \in F_0$ have to be defined where:

$$x_{jk} = \begin{cases} 1 & \text{if field } k \text{ is immediately processed after field } j \\ 0 & \text{otherwise} \end{cases}$$

Having as objective function the makespan time, which mathematically is written as $C_{\max} = \max_{j \in F}\{s_{|M|j} + o_{|M|j}\}$, the scheduling problem can be stated as:

$$\text{Minimise } C_{\max} \tag{1}$$

$$\text{Subject to}$$

$$\sum_{j \in Fo} x_{jk} = 1 \quad k \in F_0 \tag{2}$$

$$\sum_{k \in Fo} x_{jk} = 1 \quad j \in F_0 \tag{3}$$

$$s_{ij} + o_{ij} + t_{ijk} \leqslant s_{ij} + U_i(1 - x_{jk}) \quad i \in M; \quad j,k \in F \tag{4}$$

$$s_{|M|j} + o_{|M|j} \leqslant C_{\max} \quad j \in F \tag{5}$$

$$s_{ij} + o_{ij} \leqslant s_{i+1,j} \quad i \in M \setminus \{|M|\}, \quad j \in F \tag{6}$$

$$x_{jk} \in \{0,1\} \quad j,k \in F_0, \quad j \neq k \tag{7}$$

$$s_{ij} \geqslant L_{ij} \quad i \in M, \quad j \in F \tag{8}$$

Eqs. (2) and (3) ensure that in the sequence of the visited fields (including depot as a virtual field) there is always a predecessor and a successor field (or in the case of the depot a machine will leave the depot and will return to the depot from the last visited field), Eq. (4) ensures that if the order of field j precedes the one of field k, then the starting time of the task i in the field k must not exceed the completion time of the same operation i at field j plus the corresponding travel time between the two fields. U_i denotes the upper bound on the time at which machine i finishes its operation at field $j \in F$ (see Appendix A). Eq. (5) ensures that the makespan is equal or greater than the completion time of all tasks in all fields carried out by the last machine. Eq. (6) states that one machine cannot start to operate in a field if the previous machine has not completed its task in the same field. Finally, Eq. (8) provides the limitation of a lower bound on the starting time of the operation of machine i at the field j (see Appendix A).

The following assumption complies to the formulation of the optimisation problem.

- All fields are in a state that can be operated on at time zero.
- There exists a single machinery depot from where machines departs from, when being assigned tasks, and returns to, after the completion of the assigned tasks.
- All parameters, such as tasks times and travel times, are deterministic.
- The job queue operates following the *first in first out* (*FIFO*) principle, meaning that after completion of the task in a field, the field joins the queue for the next sequential task (executed by the corresponding machine).

3. The problem instance

The problem instance presented here regards the collection (baling–loading) of cotton residues from dispersed fields and in order for the cotton residues to be used for the production of bioenergy. The operational system was used as a case study consisting of two machinery systems working in series in the dispersed fields, namely, a baling system (tractor–baler) and a loading system (fork-lift/transport truck). Consequently, the set of machines is $M = \{1,2\}$, while the makespan is given by: $C_{\max} = \max_{j \in F}\{s_{2j} + o_{2j}\}$. Although that, in general, biomass handling operations include four tasks, namely, cutting, raking, baling, and loading, the presented simple case of only two sequential tasks has been selected in order to demonstrate the feasibility of implementing the pursued approach and to provide a first indication of the expected benefits.

4. Task times prediction

The key point for the implementation of the approach is the task times prediction. Contrary to an industrial flow shop, where in the most cases the task times are known with certainty, the task