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A combined simulation and linear programming method for scheduling organic fertiliser application

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Abstract

Logistics have been used to analyse agricultural operations, such as chemical application, mineral or organic fertilisation and harvesting-handling operations. Recently, due to national or European commitments concerning livestock waste management, this waste is being applied in many crops instead of other mineral fertilisers. The organic fertiliser produced has a high availability although most of the crops it is applied to have strict timeliness issues concerning its application. Here, organic fertilizer (as liquid manure) distribution logistic system is modelled by using a combined simulation and linear programming method. The method applies in certain crops and field areas taking into account specific agronomical, legislation and other constraints with the objective of minimising the optimal annual cost. Given their direct connection with the organic fertiliser distribution, the operations of cultivation and seeding were included. In a basic scenario, the optimal cost was assessed for both crops in total cultivated area of 120 ha. Three modified scenarios are presented. The first regards one more tractor as being available and provides a reduction of 3.8% in the total annual cost in comparison with the basic scenario. In the second and third modified scenarios fields having high nitrogen demand next to the farm are considered with one or two tractors and savings of 2.5% and 6.1%, respectively, compared to the basic scenario are implied. Finally, it was concluded that the effect of distance from the manure production to the location of the fields could reduce costs by 6.5%.

Keywords: liquid manure distribution, logistics, field machinery, operations planning.

Nomenclature

LP	Linear programming	d	Number of distances
DP	Dynamic programming	r	Number of dosages
IP	Integer programming	minD	Minimum distance
MIP	Mixed-integer programming	maxD	Maximum distance
LOF	Liquid organic fertilizer	D	Nitrogen dosage
c	Number of crops		
w	Number of weeks		

1 Introduction

Over the last few decades there has been significant progress in agricultural production, on many levels. Computer-based planning, simulation and scheduling of operations in parallel with advances in agricultural machinery management are only some of them (Bochtis, Sørensen, Busato, 2014).

In order to manage and evaluate the agricultural operations, many different simulation methods and tools have been developed and demonstrated (Berruto, Busato, Bochtis, Sørensen, 2010; Berruto, Busato, Bochtis, Sørensen, 2013; Busato et al., 2013; Sørensen & Bochtis, 2010; Sørensen, 2003). In many cases, the analysis involves the optimisation of a system of operations with the objective of minimising, for example, cost or energy consumption. To this end, optimisation techniques such as linear programming (LP), dynamic programming (DP), integer programming (IP), mixed-integer programming (MIP), or various approximate methods (e.g. genetic algorithms) have been used for modelling and solving such optimisation problems (Berruto, Tortia, Gay, 2006; Butterworth, 1985; Kim, Realff, Lee, Whittaker, Furtner, 2011; van Dyken, Bakken, Skjelbred, 2010). LP has been applied in agricultural production planning in both primary and secondary sectors, in various ways, such as in land-to-crop allocation problems, modelling land-use planning targeting on sustainable development, planning sustainable agri-food supply chains, and the economic and environmental evaluation of sustainable farming practices (Wankhade, 2012; Zander and Kächele, 1999; Accorsi, Cholette, Manzini, Pini, Penazzi, 2016; Meyer-Aurich, 2005).

Scheduling tasks in agricultural operations can be of vital importance given the sensitivity of indirect (timeliness) and direct (lost profit) costs that are connected to them. Researchers have been working on scheduling of various field operations including both energy crops and agri-food crops (Bochtis et al., 2013; Bochtis, Sørensen, Green, Bartzanas, Fountas, 2010; Edwards, Sørensen, Bochtis, Munkholm, 2015; Orfanou et al., 2013). Furthermore, in the secondary sector, scheduling plays a significant role in handling or standardisation of primary products (Berruto et al., 2006).

One of the most important operations that requires scheduling efforts is the application of liquid organic fertiliser (LOF) application in the form manure to different types of fields and crops (Boland, Foster, Preckel, Jones, Joern, 1999; Keplinger and Hauck, 2006). Generally, chemical fertilisers come from mineral extraction and they are enriched with nutrients in a concentrated form that make them more easily available to plants. On the other hand, organic fertilisers are made from natural materials composition such as animal or plant materials and mined minerals, with almost no processing. In this case, nutrients are released slowly compared to chemical fertilisers by natural biological processes and they have relatively low concentrations. There are various methods used to apply LOF to a field area. They include; disk injectors that formulates a furrow where the fertilizer is set by a hose, chisel injectors that haul a C-shape shank into the soil where a hose injects the fertiliser and by surface banding of organic fertiliser that is implemented by, for example, by drag hoses.

LOF application contributes mainly to environmental degradation given that the nutrients incorporated in this type of fertiliser are often higher than the recommended amounts needed to satisfy crop requirements (Ogg, 1999). In this case, the excess amount of nitrogen may drain to the groundwater, and as a consequence, this may cause problems. In parallel, eutrophication of fresh waters may be caused by phosphorus runoff (Sharpley and Rekolainen, 1997). The European Union with national and regional laws and regulations (Nitrates directive - 91/676/EEC) has established timeline restrictions that determine the best possible period for LOF application, and has set limits on the applied quantity of nitrogen to be distributed per certain field area (ha). The European directive along with national and regional laws determines time limitation for application, and they set limits for nitrogen application coming from organic sources (170 kg [N] ha^{-1} for vulnerable zones and up to 340 kg [N] ha^{-1} for non-vulnerable zones). It is important to know the concentration of nitrogen in the LOF to be applied. Time availability of the LOF and time limitation of nitrogen are connected given that the LOF is produced throughout the whole year, and it should be available in the right volume for the period that nitrogen can be applied on a specific crop given the agronomic and legal restrictions that apply.

The objective of this study is to develop a method that can be used for scheduling the problem of LOF (here refering to liquid manure) distribution, based on the combined use of a simulation model and a linear programming (LP) model, under specific agronomic and technical regulations, and timeliness restrictions. Also, this study focuses on the assessment of the usability of this method by an application on various crops under different scenarios (combining various configurations of field areas and nitrogen dosages). It focuses on the analysis of the effect of the distances between the LOF production facilities and the field areas on the total operational minimum cost.

The structure of the present work is as follows: initially, the design of methodology for the LP model is introduced given the specific problem; this is followed by the results section, where a case study regarding two different crops is provided together with the extracted solutions according to the LP model; three modified scenarios and the effect of distance on the optimal cost are discussed, and the work is wrapped up with the discussion of the results and conclusions.

2 Materials and Methods

2.1 Problem description

The current study includes the distribution of liquid organic fertilizer (LOF) in specific field areas in connection with the cultivation and seeding operation on the same areas. This was followed given the particular feature of the LOF to lose much of its chemical composition if it is not incorporated directly into the soil of the field. Regarding LOF distribution, the current study was based on the simulation model of Berruto et al. (2013) regarding operational time (h ha^{-1}), and distribution costs (€ ha^{-1}). The simulation was related to assessing the distribution cost of LOF to the field located from 1-10 km distance from the plant, with field areas varying from 2-6 ha , and nitrogen applications ranging from 50-340 kg [N] ha^{-1}. As for field cultivation , and seeding operation, inputs concerning operational time and cost were based on the results of Sopegno et al. (2016). The tool allows calculating operation cost based on field areas and field distance. Based on these results and under specific constraints (e.g. maximum working hours per week, area to be operated, seeding penalty cost etc.), the current study includes the description of the design of the LP model , and its application on the case study of LOF distribution with the objective of the minimising cost.

2.2 LP model formulation

2.2.1 Variables

The primary objective of the problem is the optimal distribution of LOF according to specific agricultural, technical and legislative constraints as described below. For this reason, the main factors described in the LP model are crops, time (weeks), distances (from field-to-LOF production location) and nitrogen dosages (higher nitrogen dosages imply larger volume of manure to be applied to the field). These factors ((1) – (3)) are connected with the main decision variables and presented below:

XX_{ijkl} LOF application area (ha) for crop C_i $where\ i \in \{1,2,\dots,c\}$, week W_j $where\ j \in \{1,2,\dots,w\}$, distance $k \in \{minD,\dots,maxD\}$, and dosage $l \in \{D_1, D_2, \dots\}$ (1)

CC_{ijkl} Cultivated field area (ha) for crop C_i $where\ i \in \{1,2,\dots,\}$, week W_j $where\ j \in \{1,2,\dots,w\}$, distance $k \in \{minD,\dots,maxD\}$, and dosage $l \in \{D_1, D_2, \dots\}$ (2)

SS_{ijkl} Seeded field area (ha) for crop C_i $where\ i \in \{1,2,\dots,m\}$, week W_j $where\ j \in \{1,2,\dots,w\}$, distance $k \in \{minD,\dots,maxD\}$, and dosage $l \in \{D_1, D_2,\dots\}$ (3)

These three decision variables drive all the other variables in the LP model as they are presented below:

$HaFarm_{ijk}$	Field area (ha) to be operated for crop C_i $where$ $i \in \{1,2,\dots,c\}$, distance $j \in \{minD,\dots,maxD\}$, and dosage $k \in \{D_1, D_2, \dots\}$
$SlProd_i$	Produced LOF (m^3) on week W_j $where$ $j \in \{1,2,\dots,w\}$
$SeWT_{ij}$	Seeding working time ($h \cdot ha^{-1}$) for crop C_i $where$ $i \in \{1,2,\dots,c\}$ and distance $j \in \{minD,\dots,maxD\}$
$CuWT_{ij}$	Cultivating working time ($h \cdot ha^{-1}$) for crop C_i $where$ $i \in \{1,2,\dots,c\}$ and distance $j \in \{minD,\dots,maxD\}$
$SlWT_{ij}$	Fertilizing working time ($h \cdot ha^{-1}$) for dosage $i \in \{D_1, D_2, \dots\}$, and distance $j \in \{minD,\dots,maxD\}$
$SlLogC_{ij}$	Fertilizing logistics cost (€$\cdot ha^{-1}$) at dosage $i \in \{D_1, D_2, \dots\}$, and distance $j \in \{minD,\dots,maxD\}$
CuC_{ij}	Cultivating cost (€$\cdot ha^{-1}$) for crop C_i $where$ $i \in \{1,2,\dots,c\}$ and distance $j \in \{minD,\dots,maxD\}$
SeC_{ij}	Seeding cost (€$\cdot ha^{-1}$) for crop C_i $where$ $i \in \{1,2,\dots,c\}$ and distance $j \in \{minD,\dots,maxD\}$
UC_i	Lost profit from undone field area (€) for crop C_i $where$ $i \in \{1,2,\dots,c\}$
$SlNC_j$	Nitrogen content of LOF on week W_j $where$ $j \in \{1,2,\dots,w\}$
$SeP_j = \begin{cases} 1 \\ 0 \end{cases}$	- If seeding is performed on week W_j $where$ $j \in \{1,2,\dots,w\}$ - otherwise
$CuP_j = \begin{cases} 1 \\ 0 \end{cases}$	- If cultivating is performed on week W_j $where$ $j \in \{1,2,\dots,w\}$ - otherwise
$SlPC_j = \begin{cases} 1 \\ 0 \end{cases}$	- If LOF is applied on week W_j $where$ $j \in \{1,2,\dots,w\}$ on corn - otherwise
$SlPW_j = \begin{cases} 1 \\ 0 \end{cases}$	- If LOF is applied on week W_j $where$ $j \in \{1,2,\dots,w\}$ on wheat - otherwise
$MaxTH_j$	Maximum workability of tractor (h) on week W_j $where$ $j \in \{1,2,\dots,w\}$

Pen_{ij}	Penalty if the operation is held on the right time crop C_i $where$ $i \in \{1,2,\dots,c\}$, week W_j $where$ $j \in \{1,2,\dots,w\}$
Se_{ijkl}	Total seeded field area (ha) for crop C_i $where$ $i \in \{1,2,\dots,c\}$, week W_j $where$ $j \in \{1,2,\dots,w\}$, distance $k \in \{minD,\dots,maxD\}$, and dosage $l \in \{D_1, D_2,\dots\}$
Cu_{ijkl}	Total cultivated field area (ha) for crop C_i $where$ $i \in \{1,2,\dots,c\}$, week W_j $where$ $j \in \{1,2,\dots,w\}$, distance $k \in \{minD,\dots,maxD\}$, and dosage $l \in \{D_1, D_2,\dots\}$
Sl_{ijkl}	Total field area applied with LOF (ha) for crop C_i $where$ $i \in \{1,2,\dots,c\}$, week W_j $where$ $j \in \{1,2,\dots,w\}$, distance $k \in \{minD,\dots,maxD\}$, and dosage $l \in \{D_1, D_2,\dots\}$
T_j	Level of total LOF (m^3) in the farm at week W_j $where$ $j \in \{0,1,\dots,w\}$
TSe_j	Tractor hours on seeding at week W_j $where$ $j \in \{1,2,\dots,w\}$
TCu_j	Tractor hours on cultivating at week W_j $where$ $j \in \{1,2,\dots,w\}$
TSl_j	Tractor hours on LOF application at week W_j $where$ $j \in \{1,2,\dots,w\}$
$HaUndo_{ijk}$	Undone field area (ha) for crop C_i $where$ $i \in \{1,2,\dots,c\}$, distance $j \in \{minD,\dots,maxD\}$, and dosage $k \in \{D_1, D_2,\dots\}$

2.2.2 Objective function and constraints

To optimise the operations connected in the model with the application of LOF, cultivation and seeding, the selected approach was to minimise the cost of the operations. The objective function of the optimisation problem refers to the cost of the three operations (application of LOF, cultivation and seeding) and the cost related to the area that due to binding constraints is not treated ($HaUndo_{ijk}$) and corresponds to the lost profit of the cultivated crop.

In addition, the objective function considers a percentage of lost profit per each week before or after the optimal operational period. The specific presentences used here are those defined in ASAE (2011).

Based on the above, the objective function of the LP program is written as:

$$\begin{aligned} minimise \quad & \sum_{i=1}^{c}\sum_{j=1}^{w}\sum_{k=1}^{d}\sum_{l=1}^{r}(CC_{ijkl} * CuC_{ik} + SS_{ijkl} * SeC_{ik}) \\ & + \sum_{i=1}^{c}\sum_{j=1}^{w}\sum_{k=1}^{d}\left(HaUndo_{ijk} * UC_i\right) \\ & + \sum_{i=1}^{c}\sum_{j=1}^{w}\sum_{k=1}^{d}\sum_{l=1}^{r}(XX_{ijkl} * SlLogC_{lk}) \\ & + \sum_{i=1}^{c}\sum_{j=1}^{w}\sum_{k=1}^{d}\sum_{l=1}^{r}(SS_{ijkl} * UC_i * Pen_{ij}) \end{aligned} \tag{4}$$

$$subject\ to \quad Se_{ijkl} = 0 \ \ \forall i \in \{1,2,\dots,c\}, j \in \{0,1,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2, \dots\}, j = 0 \tag{5}$$

$$Cu_{ijkl} = 0 \ \ \forall i \in \{1,2,\dots,c\}, j \in \{0,1,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2, \dots\}, j = 0 \tag{6}$$

$$Sl_{ijkl} = 0 \ \ \forall i \in \{1,2,\dots,c\}, j \in \{0,1,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2, \dots\}, j = 0 \tag{7}$$

$$Se_{ijkl} = Se_{ij-1kl} + SS_{ijkl} \ \ \forall i \in \{1,2,\dots,c\}, \forall j \in \{1,2\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2, \dots\} \tag{8}$$

$$Cu_{ijkl} = Cu_{ij-1kl} + CC_{ijkl} \ \ \forall i \in \{1,2,\dots,c\}, \forall j \in \{1,2,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2, \dots\} \tag{9}$$

$$Sl_{ijkl} = Sl_{ij-1kl} + XX_{ijkl} \ \ \forall i \in \{1,2,\dots,c\}, \forall j \in \{1,2,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2, \dots\} \tag{10}$$

$$T_j = T_{j-1} + SlProd_j - \sum_{i=1}^{c}\sum_{j=1}^{w}\sum_{k=1}^{d}\sum_{l=1}^{r} XX_{ijkl} * \frac{l}{SlNC_j} \;\forall i \in \{1,2,\dots,c\}, \forall j \in \{1,2,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2,\dots\} \quad (11)$$

Constraints (5) - (7) reset to zero the inventory for seeding operation, field cultivation and LOF application, respectively at the beginning of the simulation period. The accumulated inventory for seeding operation, field cultivating and LOF application for the rest of the weeks of the simulation are expressed by constraints (8) - (10), respectively. In parallel, constraint (11) regards on the progressive amount of LOF in the tank at the farm location, in order to proceed with LOF application only when there is sufficient LOF stored in the farm.

$$Se_{ijkl} \le Cu_{ij-1kl} \;\forall i \in \{1,2,\dots,c\}, \forall j \in \{1,2,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2,\dots\} \quad (12)$$

$$Cu_{ijkl} \le Sl_{ij-1kl} \;\forall i \in \{1,2,\dots,c\}, \forall j \in \{1,2,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2,\dots\} \quad (13)$$

$$Se_{ijkl} + HaUndo_{ikl} \ge HaFarm_{ikl} \;\forall i \in \{1,2,\dots,c\}, j \in \{1,2,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2,\dots\}, j = 52 \quad (14)$$

$$Cu_{ijkl} + HaUndo_{ikl} \ge HaFarm_{ikl} \;\forall i \in \{1,2,\dots,c\}, j \in \{1,2,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2,\dots\}, j = 52 \quad (15)$$

$$Sl_{ijkl} + HaUndo_{ikl} \ge HaFarm_{ikl} \;\forall i \in \{1,2,\dots,c\}, j \in \{1,2,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2,\dots\}, j = 52 \quad (16)$$

The total seeded area at a specific week should coincident with the total cultivated area of the previous week. This is ensured by inequality (12). In the same way, the total cultivated area at a specific week should be the same as the total area where LOF has been applied during the precursory week (inequality (13)). Inequalities (14) - (16) describes the condition that all areas should have been seeded, cultivated and fertilised, including also the field areas that are not operated, due to some binding constraints.

$$TSe_j = \sum_{i=1}^{c}\sum_{j=1}^{w}\sum_{k=1}^{d}\sum_{l=1}^{r} SS_{ijkl} * SeWT_{ik} \ \forall i \in \{1,2,\dots,c\}, \forall j \in \{1,2,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2, \dots\} \tag{17}$$

$$TCu_j = \sum_{i=1}^{c}\sum_{j=1}^{w}\sum_{k=1}^{d}\sum_{l=1}^{r} CC_{ijkl} * CuWT_{ik} \ \forall i \in \{1,2,\dots,c\}, \forall j \in \{1,2,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2, \dots\} \tag{18}$$

$$TSl_j = \sum_{i=1}^{c}\sum_{j=1}^{w}\sum_{k=1}^{d}\sum_{l=1}^{r} XX_{ijkl} * SlWT_{lk} \ \forall i \in \{1,2,\dots,c\}, \forall j \in \{1,2,\dots,w\}, \forall k \in \{minD,\dots,maxD\}, \forall l \in \{D_1, D_2, \dots\} \tag{19}$$

$$TSe_i \leq MaxTH_i * SeP_i \ \forall i \in \{1,2,\dots,w\} \tag{20}$$

$$TCu_i \leq MaxTH_i * CuP_i \ \forall i \in \{1,2,\dots,w\} \tag{21}$$

$$TSl_i \leq MaxTH_i * SlPC_i + MaxTH_i * SlPW_i \ \forall i \in \{1,2,\dots,w\} \tag{22}$$

$$TSe_i + TCu_i + TSl_i \leq MaxTH_i \ \forall i \in \{1,2,\dots,w\} \tag{23}$$

Equations (17) - (19) give the summation of the working hours that the tractor is engaged in seeding operations, field cultivations and LOF applications, respectively. The tractor working hours are subject to the operation readiness – if an operation can be performed on a certain week or not. This restriction applies to seeding operation, field cultivation and LOF application, respectively (inequalities (20) – (22)). Finally, inequality (23) regard on the restriction that the total hours of the tractor in all field operations should not exceed the maximum workability per week as presented in Table 2.

3 Results and Discussion

In order to execute the MIP model the IBM ILOG CPLEX Optimisation Studio® (IBM, New York, United States of America, Version 12.7.1.0) software was used. The basic characteristics of the portable computer that was used were: Intel Core i7 processor at 2.5 GHz, 16 GB RAM running at 64-bit with Windows 10 software. The processing time for the MIP model in the basic scenario was app. 5 s.

3.1 Case Study Description

In order to evaluate the current scheduling problem, results from our earlier published work regarding the comparison of distribution systems for biogas plant residual were included (Berruto, Busato, Bochtis, Sørensen, 2013).This work focused on the design of the logistics and the estimation of the costs of different transport scenarios for the application of organic fertiliser on fields. Within the available time window for each operation, a combination of the abovementioned results (presented also below in Table 4 and Table 6) from simulation and a configuration of the above described LP model were used to generate the optimal solution of the stated scheduling problem. The calculation was carried out according to certain timeliness and legal restrictions. The time unit implemented in the LP model was a period of one week. It was assumed that the LOF was produced by a pig farm unit. The LOF was assumed to be applied on specific crops, namely corn and wheat. The testing period for both crops was considered to be from January to December of a current year (52 weeks).

The simulation experiments regard a total area of 120 ha, where the operations of LOF application, cultivation and seeding take place. The selected crops shared equally the total field area (60 ha each). As presented in Table 1, 36 ha of the 60 ha allocated to corn was considered an area of nitrogen-sensitive soil where a low dosage of 170 kg [N] ha^{-1} has to be applied, while the rest 24 ha was considered as a non-nitrogen-sensitive soil area where a high dosage of 340 kg [N] ha^{-1} has to be applied. For the case of wheat, for the total allocated field area (60 ha) was considered a low dose of 170 kg [N] ha^{-1} to be applied according to crop cultivation needs and efficiency of distribution.

Table 1: Field areas (ha) per crop and nitrogen dosage for different farm-to-field distances.

Nitrogen dosage (kg [N] ha^{-1}**)**	**Crop**	**Distance (km)**				
		1	**2**	**3**	**4**	**5**
170	Corn	12	12	12	-	-
	Wheat	12	12	12	12	12
340	Corn	-	-	-	12	12

Also, other constraints were taken into account on a weekly basis. These are connected to the workability of each operation as it is shown in the Gantt chart of Fig. 1. Moreover, there was a penalty factor regarding the period that a crop can be seeded. This penalty is presented in Fig. 1 as two different coloured lines on a scale from 0 (no penalty) up to 1 (high penalty) on a monthly basis for each crop. It is based on operational and weather constraints, and it was adjusted according to specific values of ASABE Standards regarding the timeliness of field operations. This penalty factor is connected to a timeliness coefficient that is a factor that permits computation of timeliness costs (ASAE, 2011). This factor assumes linear timeliness costs with calendar days and is expressed as a decimal of maximum value of the crop per unit area per day either before or after the optimum day. In our case study, this factor was evaluated as the average value in a weekly basis and presented in a monthly basis (Fig. 1).

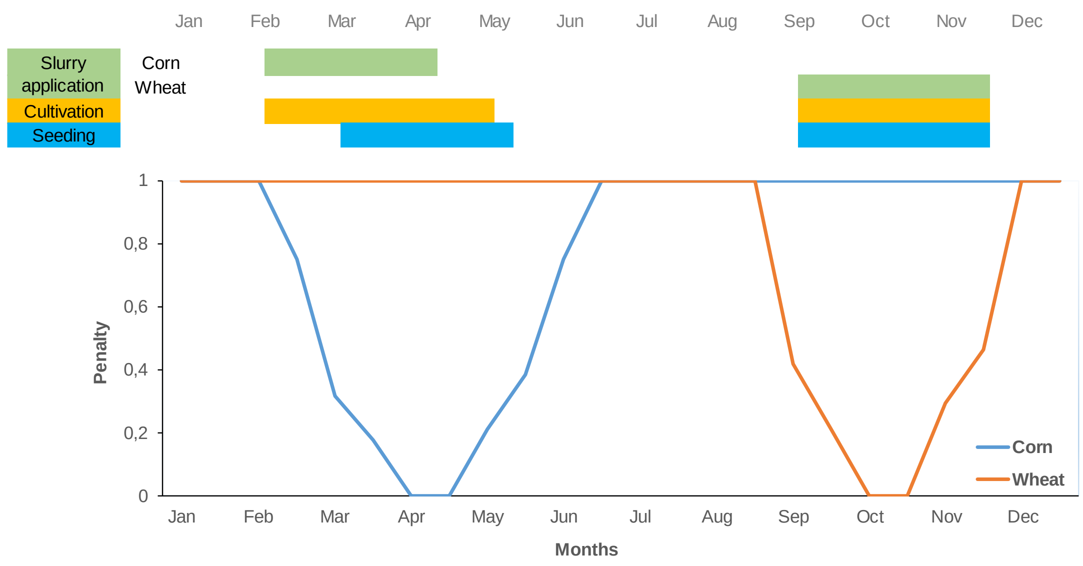

Fig. 1: Field operations (bars) and seeding penalty (lines) in monthly basis

Finally, specific assumptions were taken into account:

- The maximum operating hours of the tractor are defined for each week and were assumed to be the same for each week.
- There is initial LOF storage at the beginning of the testing period (Table 2) in a volume that is not limiting the operation.
- The LOF quantity produced at the farm is the same each week.
- The total volume of LOF is distributed through a single pass and regards the upper nitrogen bound per field area and crop.

3.2 Inputs

Table 2 lists the group of inputs that are connected to machinery use, LOF application and other parameters that were incorporated in the LP model.

Table 2: Machinery and other inputs included in the LP model

Machinery Inputs	**Other Inputs**

Crops	Maximum Workability (h week^{-1})	Tank Capacity (l)	Nitrogen Content in the LOF (kg m^{-3})	Reserved LOF in the farm (m^3)	LOF production on the farm (m^3 week^{-1})	Lost Profit (€ ha^{-1})
Maize	40	15,000	4.5	2300	71.9	639
Wheat						532

The operational working times (h ha^{-1}) for both cultivation (including ploughing, mineral fertilising and seedbed preparation) and seeding operations were adjusted to those reported in Sopegno et al. (2016), and they were connected to the linear programming model as an input. Table 3 presents the operating working times for both seeding and cultivation operations for distances 1-5 km. Similarly, the fertilisation working times (h ha^{-1}) were adopted by the simulation model used in Berruto et al. (2013) for three different nitrogen dosages and different distances, and they were used as an input in the LP model (Table 4).

Table 3: Operational working time (h ha^{-1}) for various distances (km) in both crops*

Distance (km)		**1**	**2**	**3**	**4**	**5**
Seeding	Maize	0.83	0.87	0.91	0.96	1.00
	Wheat	1.39	1.43	1.47	1.52	1.56
Cultivation	Maize	3.73	3.77	3.81	3.86	3.90
	Wheat	2.81	2.85	2.89	2.94	2.98

*Adopted from Sopegno et al. (2016)

Table 4: Fertilising working time (h ha^{-1}) in various distances (km) and dosages (kg [N] ha^{-1})*

Nitrogen Dosage	**Distance (km)**				
(kg [N] ha^{-1}**)**	**1**	**2**	**3**	**4**	**5**

170	1.05	1.24	1.37	1.48	1.61
250	1.52	1.81	2.00	2.18	2.38
340	1.95	2.33	2.58	2.81	3.07

*Adopted from Berruto et al. (2013)

Given the operational working time for field cultivation and seeding, the corresponding operational costs (€ ha^{-1}) were calculated and presented in Table 5.

Table 5: Operational cost (€ ha^{-1}) for various distances in both crops*

Distance (km)		**1**	**2**	**3**	**4**	**5**
Seeding	Maize	27.00	28.35	29.69	31.03	32.37
	Wheat	53.40	54.98	56.57	58.15	59.74
Cultivation	Maize	126.91	128.32	129.72	131.13	132.53
	Wheat	97.56	99.00	100.43	101.86	103.30

*Adopted from Sopegno et al. (2016)

The fertilising logistics cost (€ ha^{-1}) was calculated according to the distribution cost of Berruto et al. (2013), and it is presented in Table 6 for variable nitrogen dosages and distances.

Table 6: Fertilizing logistics cost (€·ha^{-1}) in various distances (km) and dosages (kg [N] ha^{-1})*

Nitrogen dosage (kg [N] ha^{-1})	**Distance (km)**				
	1	**2**	**3**	**4**	**5**
170	109.23	129.44	142.61	154.13	167.83
250	158.53	189.17	209.08	227.40	248.35
340	203.52	243.00	269.15	292.63	319.88

*Adopted from Berruto et al. (2013)

3.3 LP Model Results

3.3.1 The basic scenario

The LP model generates results for every field operation (i.e. LOF application, cultivation and seeding) for each specific week and crop in specific field areas. In the basic scenario the optimal solution, i.e. the minimum cost, for the execution of these field operations was estimated to €43,586. According to the results of the model, there is a field area equal to 1.88 ha of wheat total field area that was not cultivated. The non-cultivated area derived from the fact that only one tractor was available to carry all field operations, and it was too costly (for both penalty and distance reasons) to cultivate this area.

Hereafter, the results regarding the optimal exploitation period (in weeks) for maize and wheat as they extracted from the LP model, are presented in Table 7 and Table 8 for corn and wheat, respectively.

Table 7: Results per operation on a weekly basis for corn field areas

Week A/N	Stored LOF (m^3)	Distributed LOF (m^3)	Fert. area (ha)	Cult. area (ha)	Seeded area (ha)	Tractor Fert. Use (h)	Tractor Cult. Use (h)	Tractor Seed Use (h)
8	2,731	-	13.57	-	-	40.00	-	-
9	2,803	-	5.64	6.20	-	15.85	24.15	-
10	1,850	1,025	12	6.49	-	14.91	25.09	-
11	1,496	426	-	10.60	-	-	40.00	-
12	1,114	453	10.87	6.52	-	14.88	25.12	-
13	1,186	-	6.52	8.60	-	7.19	32.81	-
14	847	411	6.61	8.79	-	6.93	33.07	-
15	673	246	-	8.01	10.22	-	29.94	10.06
16	495	250	-	-	44.99	-	-	40.00
17	567	-	4.79	-	-	14.70	-	-
18	639	-	-	4.79	-	-	18.66	-
19	349	362	-	-	4.79	-	-	4.77
TOTAL	14,750	3,173	60	60	60	114.46	228.84	54.83

Table 8: Results per operation in a weekly basis for wheat field areas

Week A/N	Stored LOF (m^3)	Distributed LOF (m^3)	Fertilized area (ha)	Cult. area (ha)	Seeded area (ha)	Tractor Fert. Use (h)	Tractor Cult. Use (h)	Tractor Seed Use (h)
38	634	1,225	32.41		-	40.00	-	-
39	495	211	5.59	11.42	-	6.94	33.06	-
40	567	-	-	14.05	-	-	40.00	-
41	639	-	-	9.95	8.46	-	27.97	12.03
42	676	35	0.93	-	26.96	1.31	-	38.69
43	23	725	19.18	3.52	-	29.71	10.29	-
44	95	-	-	11.78	3.52	-	34.70	5.30
45	166	-	-	7.40	11.78	-	22.03	17.97
46	238	-	-	-	7.40	-	-	11.52
TOTAL	3,533	2,196	58.11	58.12	58.12	77.96	168.05	85.51

3.3.2 Scenario 1

The first scenario was connected to the introduction of a second tractor to execute the total field area in both crops without having any hectare not operated. The addition of one tractor had an effect on the results of the LP model and, of course, in the optimal solution that was equal to €41,904. In this scenario, the LOF was applied in all of the field areas. The extracted results of Scenario 1 are presented in Fig. 2 for maize (left group) and wheat (right group) field areas. For both groups the LOF quantity, the field area and the tractor use per operation are depicted for the corresponding weeks of each crop. The seeding is completed three weeks in advance compared to the basic scenario. The addition of one more tractor allows more tractor hours available per week. Given an example, in Week 11 there is 40 h for cultivation and 17.81 h for LOF distribution. In the same week of the baseline scenario had 40 h in total, for cultivation operation only.

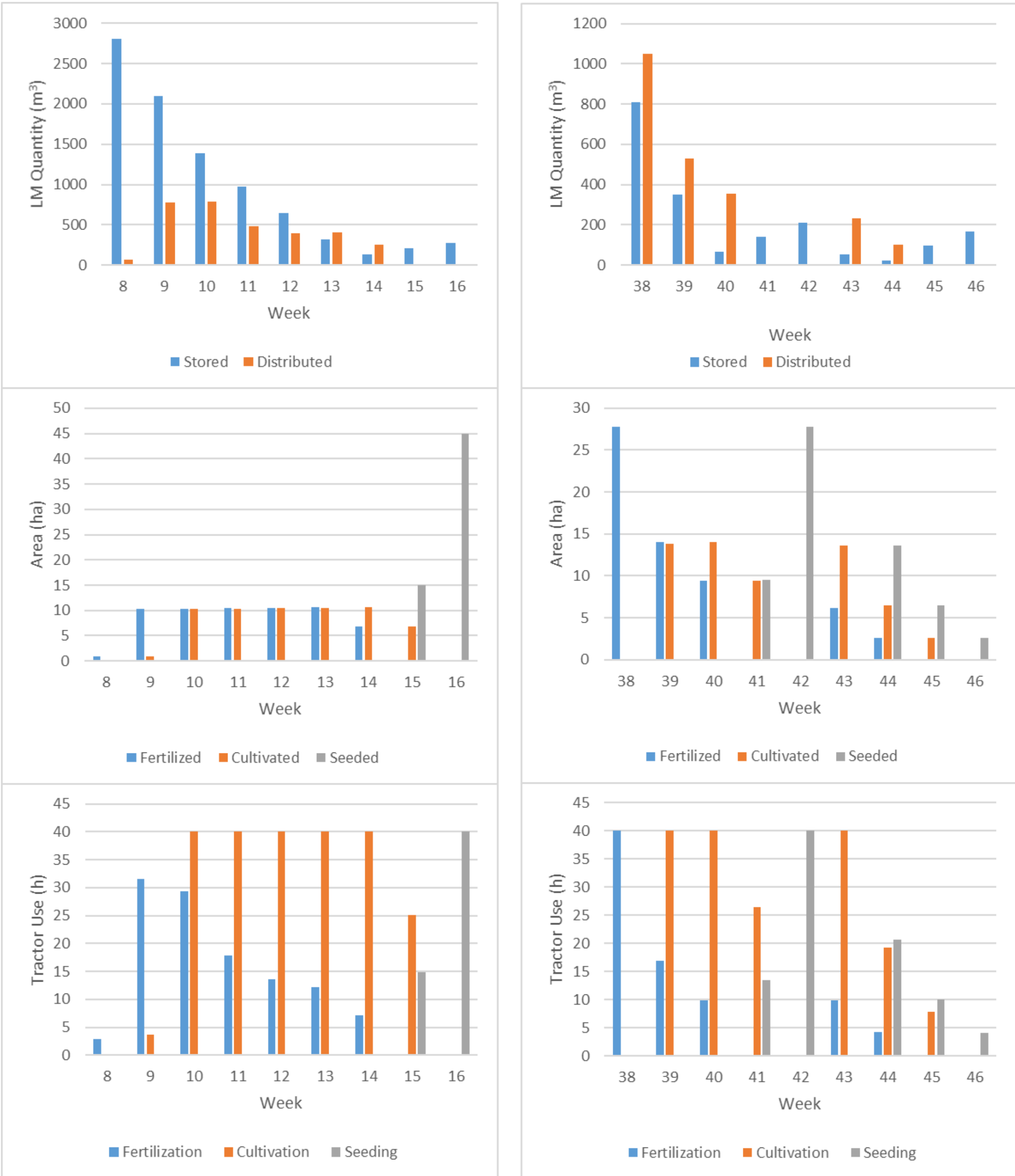

Fig. 2: Results for maize (left group) and wheat (right group) in Scenario 1

3.3.3 Scenario 2

To illustrate the possible application of the method, a second scenario assesses the optimal scheduling for a minimum cost under a different field areas' configuration regarding maize only, given that wheat does not allow to apply high nitrogen dosages due to agronomic reasons. The configuration followed in the Scenario 2 is presented in Table 9, and it was tested considering the implement of only one tractor for all operations.

Table 9: Alternative configuration of field areas per crop and distance

Nitrogen dosage (kg [N] ha^{-1})	**Crop**	**Distance (km)**				
		1	**2**	**3**	**4**	**5**
170	Maize	-	-	12	12	12
	Wheat	12	12	12	12	12
340	Maize	12	12	-	-	-

In the case of one tractor, the optimal solution of the problem of operation scheduling was €42,474 without applying LOF at 1.8 ha of wheat (~ 2% of total cost). The main percentages per operation for both crops are presented in Fig. 3.

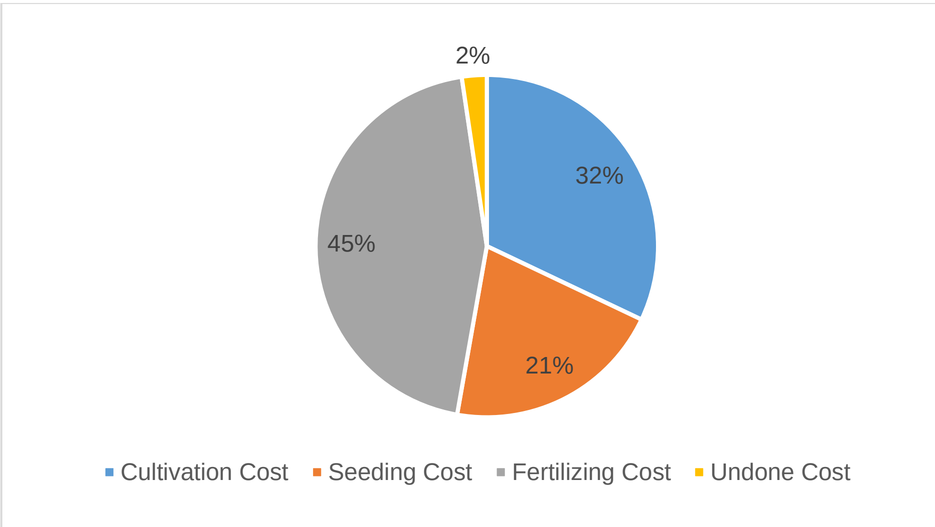

Fig. 3: Cost per operation (%) for both crops in Scenario 2

3.3.4 Scenario 3

Scenario 3 keeps the same field area configuration shown in Table 9 for Scenario 2 but two tractors are implemented for the operations execution instead of a single tractor. By implementing two tractors for the execution of the LOF application, field cultivation and seeding in the given field areas, the minimum cost was €40,912 for the total field area operations in both crops. In this scenario, the total field area is operated. In Fig. 4, the allocation of operational cost percentages are presented for both crops.

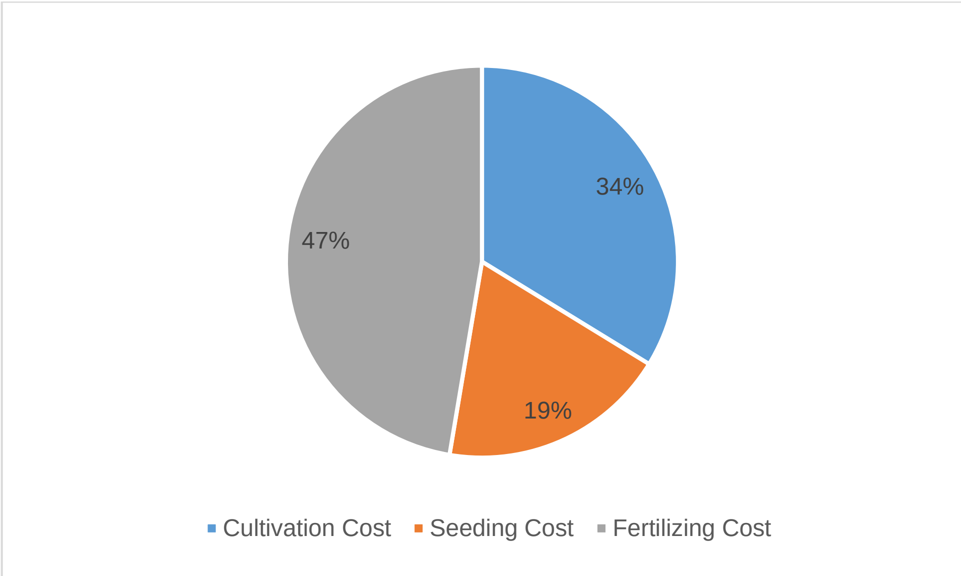

Fig. 4: Cost per operation (%) for both crops in Scenario 3

3.4 Comparison of the four scenarios

In order to evaluate better the four scenarios, they are presented graphically in Fig. 5 as a comparison in optimal minimum cost (€ y^{-1}) between the basic and the modified scenarios with one or two tractors is presented.

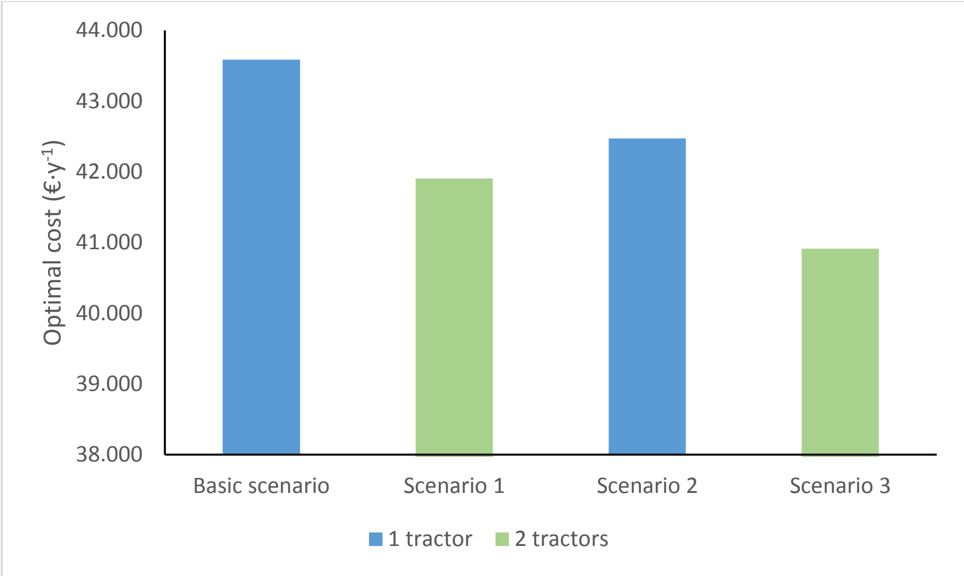

Fig. 5: Optimal cost (€ y^{-1}) for both baseline scenarios (basic and Scenario 1) and modified scenarios (Scenario 2 and 3)

3.5 The effect of distance on the total cost

For a more thorough analysis, the effect of distance on the optimal annual cost was performed. For this reason, it was assumed that the whole field area (60 ha) of both crops require a LOF dosage of 170 kg [N] ha^{-1} in distances varying from 1 to 10 km. The LP model operated this analysis by using either one or two tractors. The extracted results regarding the minimum optimal cost (€ y^{-1}) is presented in Fig. 6. The unit operational cost (not presented in the figure) is about 249 € ha^{-1} at 1 km vs about 452 € ha^{-1} at 10 km, with an increase of 81%. As is shown from Fig. 6, by using two tractors instead of one, there is a significant difference in the optimal cost varying from 681 € y^{-1} (at 1 km) up to 3,546 €·y^{-1} (at 10 km). In this case, the unit cost is about 243 € ha^{-1} at 1 km vs about 422 € ha^{-1} at 10 km, with an increase of 73%.

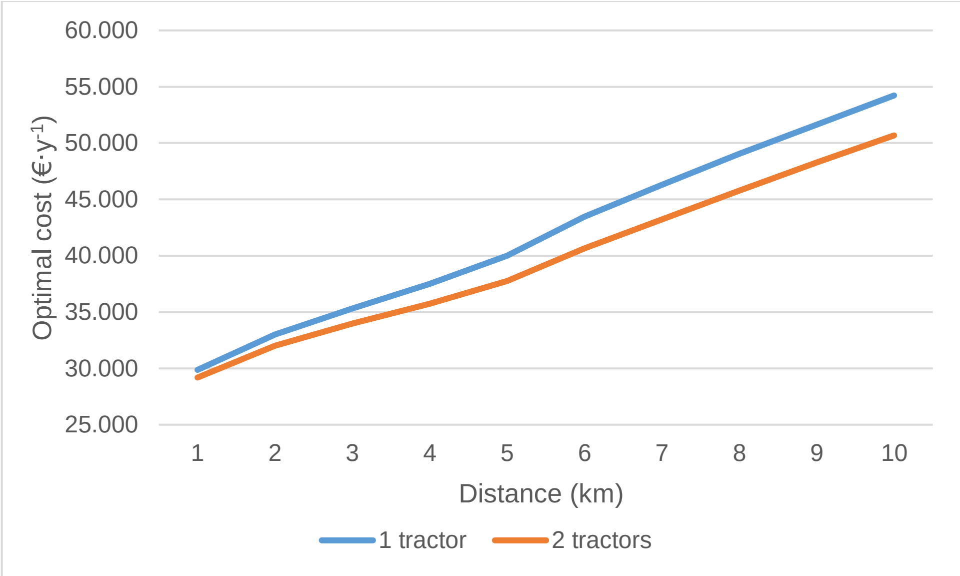

Fig. 6: The optimal total cost (€ y^{-1}) in various farm-to-field distances (km) by using one or two tractors

4 Conclusions

A combination of simulation and linear programming method was developed to optimise the time schedule for LOF application in connection with cultivation and seeding operations. A number of constraints were included given not only specific agronomical and technical regulations but also timeliness restrictions. To evaluate the usability of this method, different scenarios were assessed in two selected crops, namely maize and wheat. The basic scenario was connected to the execution of all field operations by a single tractor, and the optimal minimum cost was equal to €43,585 for the tested period (year). A second scenario (Scenario 1) was also assessed in the same field areas' configuration as the basic scenario but by using two tractors for the field operations. As a result, there is 3.85% less annual cost in the Scenario 1 compared to the basic scenario.

A modified scenario (Scenario 2) was considered, also, including a different configuration of field areas and nitrogen dosages resulting in 2.55% less annual cost compared to the basic scenario. In addition, in Scenario 3, a reduction equal to 6.13% compared to the basic scenario is presented. Finally, the effect of distance in the total minimum cost is presented by using one or two tractors. The analysis pointed out reduced optimal cost (in the case of two tractors) varying from 2.3% (in 1 km) up to 6.5% (in 10 km) increasing almost proportionally the savings in distances above 10 km.

There are specific national and European regulations regarding the amount and density of LOF that can be applied in each field crop for vulnerable and non-vulnerable soils. Further research include the implementation of weather data which highly affect the optimal cost given that on specific periods and regions the tractor workability may be quite low because of weather conditions. In this case, a decision-making model could select either to apply LOF out of the optimal period incurring penalties or leave the field areas without being applied with LOF including the lost profit. Taking into account that by using a reasonably modern computer the computational time is very low (~ 5 sec), this work has the potential to be transformed to an online tool that could include real time data and extract results close to real time. For further research, the present work can be expanded to the implementation of machinery workability measures for all the field operations annually (including harvesting operations) under the objective of minimising cost and the best scheduling of field operations.

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