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

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

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13

14 **Abstract**

15 Logistics have been used to analyse agricultural operations, such as chemical application,  
16 mineral or organic fertilisation and harvesting-handling operations. Recently, due to national  
17 or European commitments concerning livestock waste management, this waste is being  
18 applied in many crops instead of other mineral fertilisers. The organic fertiliser produced has  
19 a high availability although most of the crops it is applied to have strict timeliness issues  
20 concerning its application. Here, organic fertilizer (as liquid manure) distribution logistic  
21 system is modelled by using a combined simulation and linear programming method. The  
22 method applies in certain crops and field areas taking into account specific agronomical,  
23 legislation and other constraints with the objective of minimising the optimal annual cost.  
24 Given their direct connection with the organic fertiliser distribution, the operations of

25 cultivation and seeding were included. In a basic scenario, the optimal cost was assessed for  
 26 both crops in total cultivated area of 120 ha. Three modified scenarios are presented. The first  
 27 regards one more tractor as being available and provides a reduction of 3.8% in the total  
 28 annual cost in comparison with the basic scenario. In the second and third modified scenarios  
 29 fields having high nitrogen demand next to the farm are considered with one or two tractors  
 30 and savings of 2.5% and 6.1%, respectively, compared to the basic scenario are implied.  
 31 Finally, it was concluded that the effect of distance from the manure production to the  
 32 location of the fields could reduce costs by 6.5%.

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

<b>Nomenclature</b>				
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			

34

## 35 1 Introduction

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

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

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

62 One of the most important operations that requires scheduling efforts is the application of  
63 liquid organic fertiliser (LOF) application in the form manure to different types of fields and  
64 crops (Boland, Foster, Preckel, Jones, Joern, 1999; Keplinger and Hauck, 2006). Generally,

65 chemical fertilisers come from mineral extraction and they are enriched with nutrients in a  
66 concentrated form that make them more easily available to plants. On the other hand, organic  
67 fertilisers are made from natural materials composition such as animal or plant materials and  
68 mined minerals, with almost no processing. In this case, nutrients are released slowly  
69 compared to chemical fertilisers by natural biological processes and they have relatively low  
70 concentrations. There are various methods used to apply LOF to a field area. They include;  
71 disk injectors that formulates a furrow where the fertilizer is set by a hose, chisel injectors  
72 that haul a C-shape shank into the soil where a hose injects the fertiliser and by surface  
73 banding of organic fertiliser that is implemented by, for example, by drag hoses.

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

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

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

104

## 105 2 Materials and Methods

### 106 2.1 Problem description

107 The current study includes the distribution of liquid organic fertilizer (LOF) in specific field  
108 areas in connection with the cultivation and seeding operation on the same areas. This was  
109 followed given the particular feature of the LOF to lose much of its chemical composition if it  
110 is not incorporated directly into the soil of the field. Regarding LOF distribution, the current  
111 study was based on the simulation model of Berruto et al. (2013) regarding operational time  
112 ( $\text{h ha}^{-1}$ ), and distribution costs ( $\text{€ ha}^{-1}$ ). The simulation was related to assessing the distribution  
113 cost of LOF to the field located from 1-10 km distance from the plant, with field areas varying

114 from 2-6 ha , and nitrogen applications ranging from 50-340 kg [N] ha<sup>-1</sup>. As for field cultivation  
 115 , and seeding operation, inputs concerning operational time and cost were based on the  
 116 results of Sopegno et al. (2016). The tool allows calculating operation cost based on field areas  
 117 and field distance. Based on these results and under specific constraints (e.g. maximum  
 118 working hours per week, area to be operated, seeding penalty cost etc.), the current study  
 119 includes the description of the design of the LP model , and its application on the case study  
 120 of LOF distribution with the objective of the minimising cost.

121

## 122 2.2 LP model formulation

### 123 2.2.1 Variables

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

$$XX_{ijkl} \quad \text{LOF application area (ha) for crop } C_i \text{ where } i \in \{1,2, \dots, c\}, \text{ week} \quad (1)$$

$W_j$  where  $j \in \{1, 2, \dots, w\}$ , distance  $k \in \{minD, \dots, maxD\}$ , and dosage

$l \in \{D_1, D_2, \dots\}$

$$CC_{ijkl} \quad \text{Cultivated field area (ha) for crop } C_i \text{ where } i \in \{1,2, \dots, \}, \text{ week} \quad (2)$$

$W_j$  where  $j \in \{1, 2, \dots, w\}$ , distance  $k \in \{minD, \dots, maxD\}$ , and dosage

$l \in \{D_1, D_2, \dots\}$

$SS_{ijkl}$  Seeded field area (ha) for crop  $C_i$  where  $i \in \{1, 2, \dots, m\}$ , week (3)

$W_j$  where  $j \in \{1, 2, \dots, w\}$ , distance  $k \in \{minD, \dots, maxD\}$ , and dosage

$l \in \{D_1, D_2, \dots\}$

130 These three decision variables drive all the other variables in the LP model as they are

131 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 <sup>3</sup> ) on week $W_j$ where $j \in \{1,2, \dots, w\}$
$SeWT_{ij}$	Seeding working time (h·ha <sup>-1</sup> ) for crop $C_i$ where $i \in \{1,2, \dots, c\}$ and distance $j \in \{minD, \dots, maxD\}$
$CuWT_{ij}$	Cultivating working time (h·ha <sup>-1</sup> ) for crop $C_i$ where $i \in \{1,2, \dots, c\}$ and distance $j \in \{minD, \dots, maxD\}$
$SlWT_{ij}$	Fertilizing working time (h·ha <sup>-1</sup> ) for dosage $i \in \{D_1, D_2, \dots\}$ , and distance $j \in \{minD, \dots, maxD\}$
$SlLogC_{ij}$	Fertilizing logistics cost (€·ha <sup>-1</sup> ) at dosage $i \in \{D_1, D_2, \dots\}$ , and distance $j \in \{minD, \dots, maxD\}$
$CuC_{ij}$	Cultivating cost (€·ha <sup>-1</sup> ) for crop $C_i$ where $i \in \{1,2, \dots, c\}$ and distance $j \in \{minD, \dots, maxD\}$
$SeC_{ij}$	Seeding cost (€·ha <sup>-1</sup> ) 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 $k \in \{D_1, D_2, \dots\}$

132

### 133 2.2.2 Objective function and constraints

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

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

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

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

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

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

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

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

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

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

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

$$\in \{1,2, \dots, w\}, \forall k \in \{minD, \dots, maxD\}, \forall l \in \{D_1, D_2, \dots\}$$

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

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

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

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

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

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

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

155

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

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

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

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

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

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

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

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

### 163 3 Results and Discussion

164 In order to execute the MIP model the IBM ILOG CPLEX Optimisation Studio® (IBM, New York,  
 165 United States of America, Version 12.7.1.0) software was used. The basic characteristics of the  
 166 portable computer that was used were: Intel Core i7 processor at 2.5 GHz, 16 GB RAM running

167 at 64-bit with Windows 10 software. The processing time for the MIP model in the basic  
168 scenario was app. 5 s.

### 169 3.1 Case Study Description

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

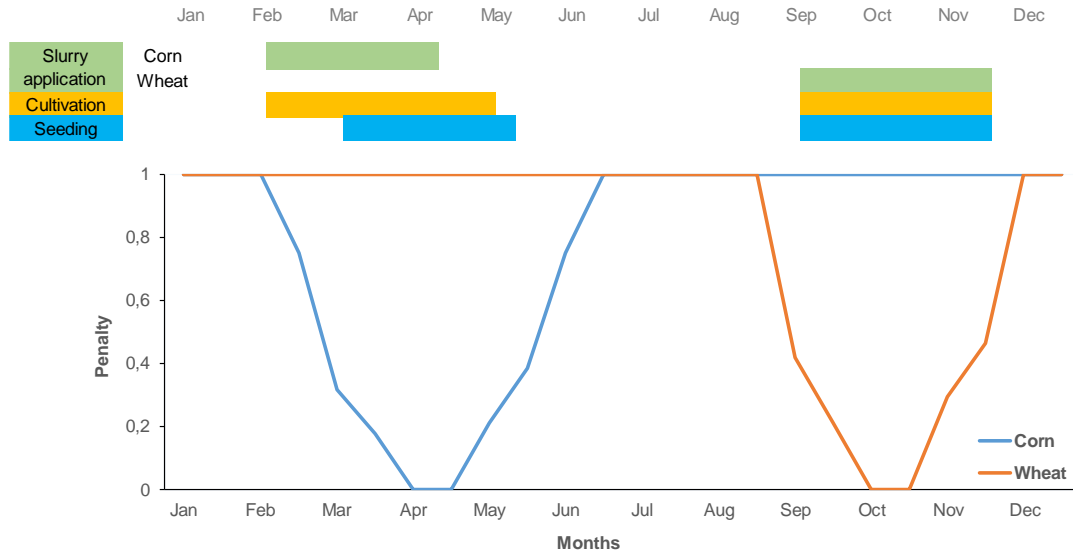
182 The simulation experiments regard a total area of 120 ha, where the operations of LOF  
183 application, cultivation and seeding take place. The selected crops shared equally the total  
184 field area (60 ha each). As presented in Table 1, 36 ha of the 60 ha allocated to corn was  
185 considered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

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

Nitrogen		Distance (km)				
dosage (kg [N] ha <sup>-1</sup> )	Crop	1	2	3	4	5
170	Corn	12	12	12	-	-
	Wheat	12	12	12	12	12
340	Corn	-	-	-	12	12

191

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



203

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

205 Finally, specific assumptions were taken into account:

- 206
- The maximum operating hours of the tractor are defined for each week and were
  - 207 assumed to be the same for each week.
  - 208
  - There is initial LOF storage at the beginning of the testing period (Table 2) in a volume
  - 209 that is not limiting the operation.
  - 210
  - The LOF quantity produced at the farm is the same each week.
  - 211
  - The total volume of LOF is distributed through a single pass and regards the upper
  - 212 nitrogen bound per field area and crop.

### 213 3.2 Inputs

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

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

Machinery Inputs	Other Inputs
------------------	--------------



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

217

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

225 **Table 3:** Operational working time (h ha<sup>-1</sup>) for various distances (km) in both crops\*

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

226

\*Adopted from Sopegno et al. (2016)

227 Table 4: Fertilising working time (h ha<sup>-1</sup>) in various distances (km) and dosages (kg [N] ha<sup>-1</sup>)\*

<b>Nitrogen Dosage (kg [N] ha<sup>-1</sup>)</b>	<b>Distance (km)</b>				
	<b>1</b>	<b>2</b>	<b>3</b>	<b>4</b>	<b>5</b>

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

228 \*Adopted from Berruto et al. (2013)

229 Given the operational working time for field cultivation and seeding, the corresponding  
230 operational costs (€ ha<sup>-1</sup>) were calculated and presented in Table 5.

231 **Table 5:** Operational cost (€ ha<sup>-1</sup>) for various distances in both crops\*

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

232 \*Adopted from Sopegno et al. (2016)

233 The fertilising logistics cost (€ ha<sup>-1</sup>) was calculated according to the distribution cost of Berruto  
234 et al. (2013), and it is presented in Table 6 for variable nitrogen dosages and distances.

235 **Table 6:** Fertilizing logistics cost (€·ha<sup>-1</sup>) in various distances (km) and dosages (kg [N] ha<sup>-1</sup>)\*

Nitrogen dosage (kg [N] ha <sup>-1</sup> )	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

236 \*Adopted from Berruto et al. (2013)

237

238 3.3 LP Model Results

239 3.3.1 The basic scenario

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

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

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

Week A/N	Stored LOF (m <sup>3</sup> )	Distributed LOF (m <sup>3</sup> )	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
<b>TOTAL</b>	<b>14,750</b>	<b>3,173</b>	<b>60</b>	<b>60</b>	<b>60</b>	<b>114.46</b>	<b>228.84</b>	<b>54.83</b>

251

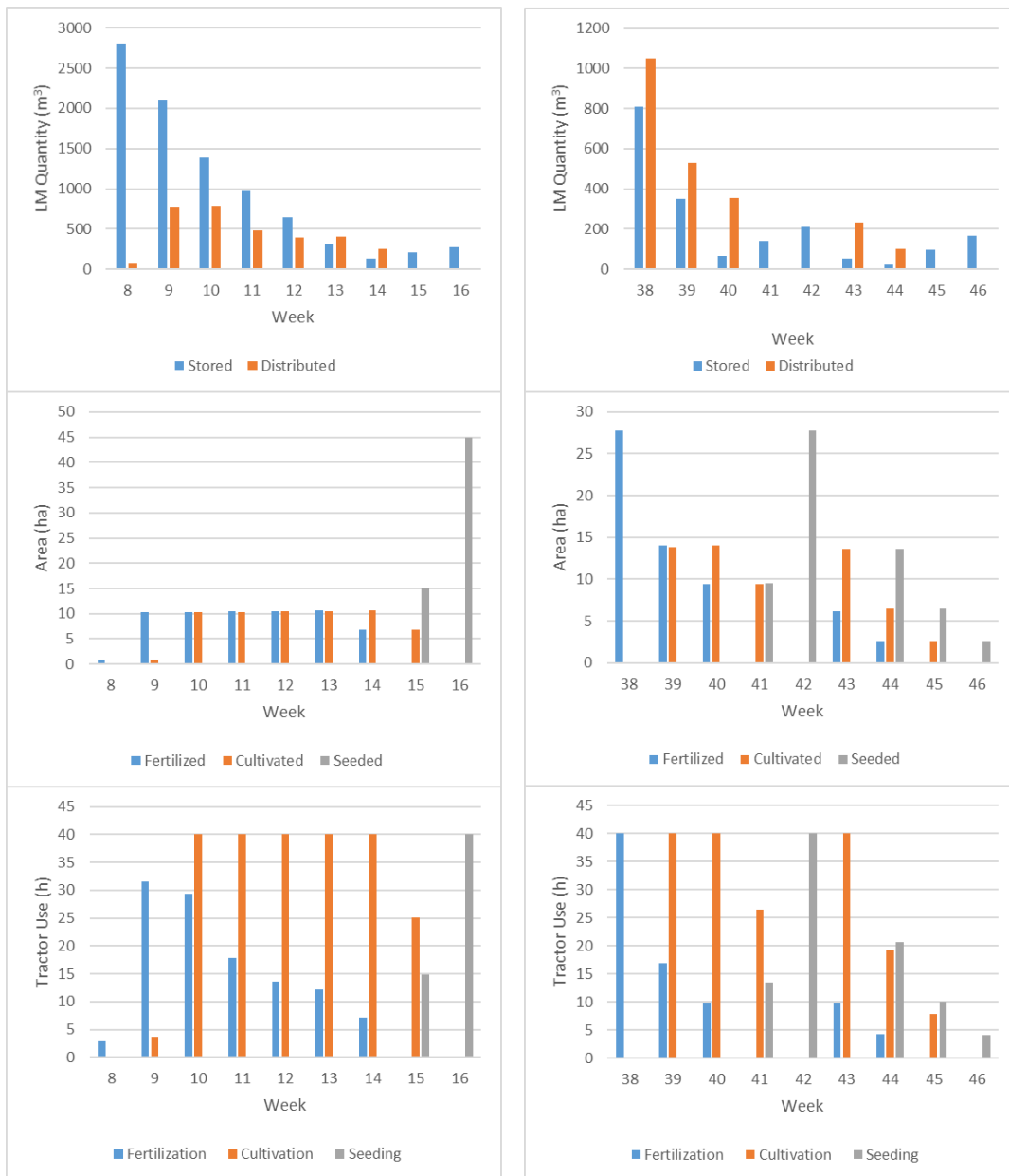
252 **Table 8:** Results per operation in a weekly basis for wheat field areas

Week A/N	Stored LOF (m <sup>3</sup> )	Distributed LOF (m <sup>3</sup> )	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
<b>TOTAL</b>	<b>3,533</b>	<b>2,196</b>	<b>58.11</b>	<b>58.12</b>	<b>58.12</b>	<b>77.96</b>	<b>168.05</b>	<b>85.51</b>

253

### 254 3.3.2 Scenario 1

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



266

267

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

268

### 269 3.3.3 Scenario 2

270 To illustrate the possible application of the method, a second scenario assesses the optimal  
 271 scheduling for a minimum cost under a different field areas' configuration regarding maize  
 272 only, given that wheat does not allow to apply high nitrogen dosages due to agronomic

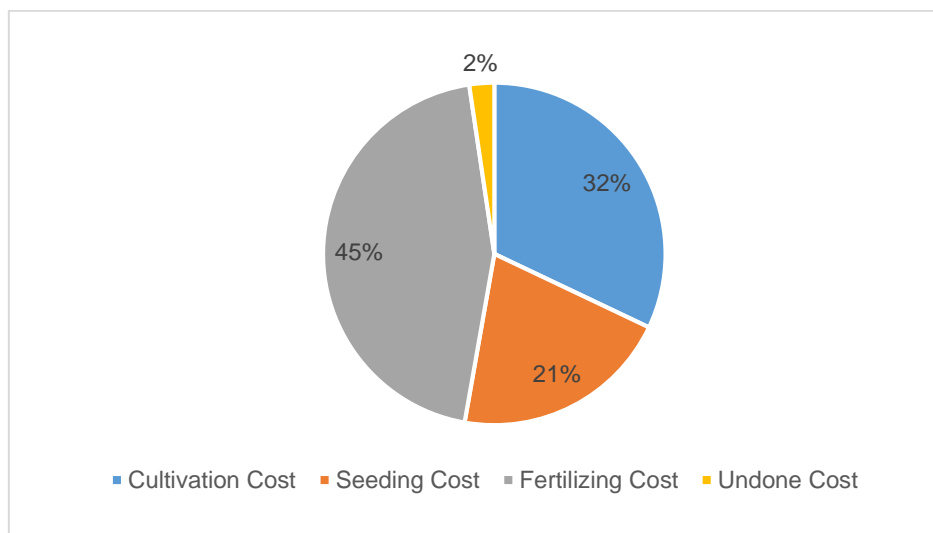
273 reasons. The configuration followed in the Scenario 2 is presented in Table 9, and it was tested  
 274 considering the implement of only one tractor for all operations.

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

Nitrogen dosage (kg [N] ha <sup>-1</sup> )	Crop	Distance (km)				
		1	2	3	4	5
170	Maize	-	-	12	12	12
	Wheat	12	12	12	12	12
340	Maize	12	12	-	-	-

276

277 In the case of one tractor, the optimal solution of the problem of operation scheduling was  
 278 €42,474 without applying LOF at 1.8 ha of wheat (~ 2% of total cost). The main percentages  
 279 per operation for both crops are presented in Fig. 3.



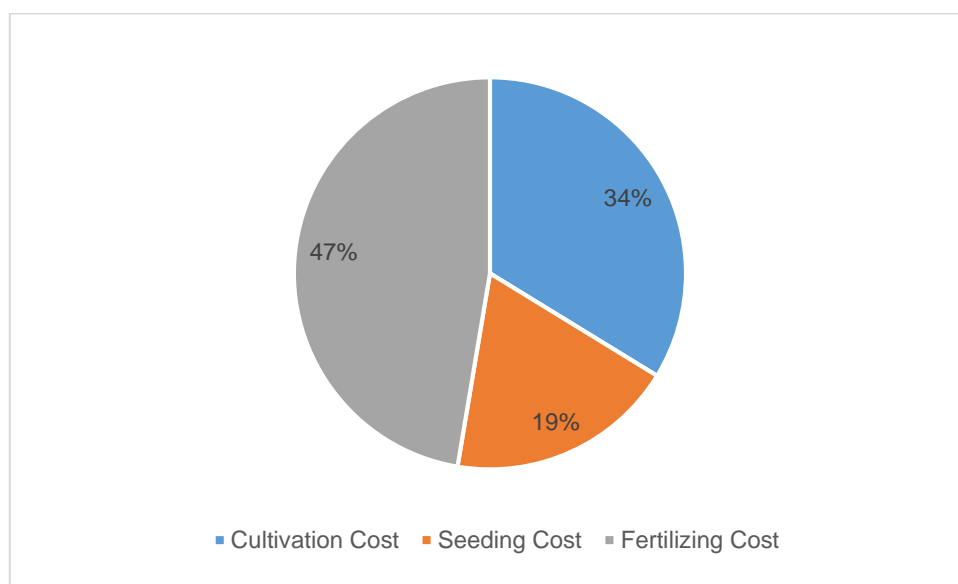
280

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

282

283 3.3.4 Scenario 3

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



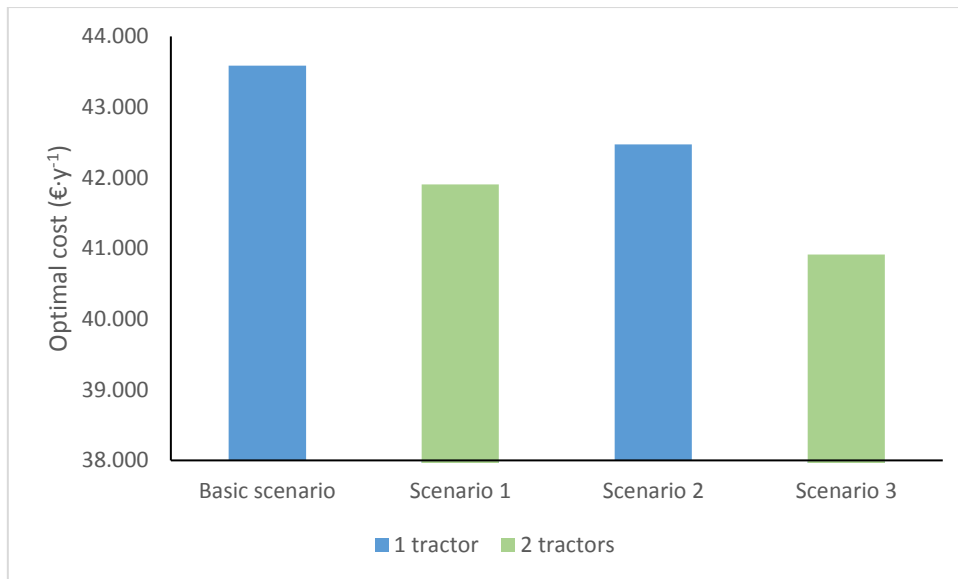
290

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

292

293 3.4 Comparison of the four scenarios

294 In order to evaluate better the four scenarios, they are presented graphically in Fig. 5 as a  
295 comparison in optimal minimum cost (€ y<sup>-1</sup>) between the basic and the modified scenarios  
296 with one or two tractors is presented.



297

298 **Fig. 5:** Optimal cost (€ y<sup>-1</sup>) for both baseline scenarios (basic and Scenario 1) and modified  
 299 scenarios (Scenario 2 and 3)

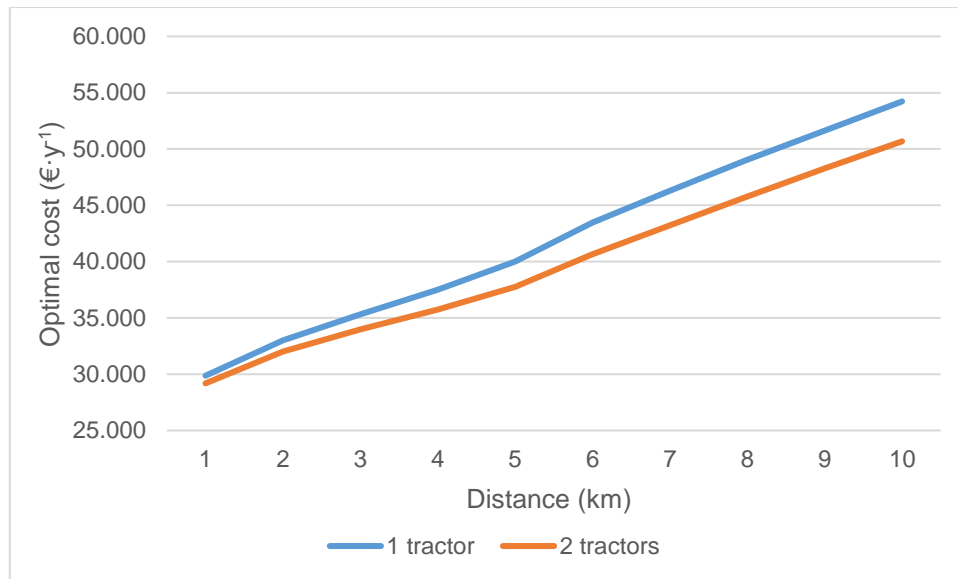
300

### 301 3.5 The effect of distance on the total cost

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

311





312

313 **Fig. 6:** The optimal total cost (€ y<sup>-1</sup>) in various farm-to-field distances (km) by using one or  
 314 two tractors

315

## 316 4 Conclusions

317 A combination of simulation and linear programming method was developed to optimise the  
 318 time schedule for LOF application in connection with cultivation and seeding operations. A  
 319 number of constraints were included given not only specific agronomical and technical  
 320 regulations but also timeliness restrictions. To evaluate the usability of this method, different  
 321 scenarios were assessed in two selected crops, namely maize and wheat. The basic scenario  
 322 was connected to the execution of all field operations by a single tractor, and the optimal  
 323 minimum cost was equal to €43,585 for the tested period (year). A second scenario (Scenario  
 324 1) was also assessed in the same field areas' configuration as the basic scenario but by using  
 325 two tractors for the field operations. As a result, there is 3.85% less annual cost in the Scenario  
 326 1 compared to the basic scenario.

327 A modified scenario (Scenario 2) was considered, also, including a different configuration of  
 328 field areas and nitrogen dosages resulting in 2.55% less annual cost compared to the basic

329 scenario. In addition, in Scenario 3, a reduction equal to 6.13% compared to the basic scenario  
330 is presented. Finally, the effect of distance in the total minimum cost is presented by using  
331 one or two tractors. The analysis pointed out reduced optimal cost (in the case of two tractors)  
332 varying from 2.3% (in 1 km) up to 6.5% (in 10 km) increasing almost proportionally the savings  
333 in distances above 10 km.

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

346

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350

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