Smart Agricultural Technology 5 (2023) 100261

Contents lists available at ScienceDirect

Smart Agricultural Technology

journal homepage: www.journals.elsevier.com/smart-agricultural-technology

Optimal use of agricultural robot in arable crop rotation: A case study from the Netherlands

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ARTICLE INFO

Keywords:
Agricultural robot
Crop farming
Field operation
Optimal use
Labour saving
Tractor
Fuel saving
the Netherlands

ABSTRACT

Acute shortages and rising costs of labour in the food and farming sector across Europe exhibit the fragility of agrifood systems. Agricultural robots present an opportunity to strengthen agrifood systems by addressing labour shortages and reduce CO_2 emissions. This study proposes a method to investigate the potential use of an autonomous robotic system based on a case study on a typical high-tech Dutch farm that implements both an agricultural robot (AGR) and a conventional tractor (TRC) on a farm of 200 hectares in the region of Oldambt. To demonstrate the optimal use of an AGR, five farming operations (seeding, catch crop seeding, tine weeding, harrowing, inter-row hoeing, and spot spraying) in a crop rotation system of five crops (sugar beets, pumpkins, onions, spring barley and winter wheat) was chosen. The agricultural robot is here considered as a supplement (not substitute) to the farms overall cropping capability. It is found that price of fuel and labour are critical factors where higher fuel and labour price increases the benefit and use of the robot. Besides, time needed for remote supervision of the robot plays an important role.

Abbreviations and acronyms

AGR	Agricultural robot
TRC	tractor
TRC REF	reference case with only tractor
AGR+TRC	combination of AGR and TRC use
MAV	maximum acquisition value
PV	Present Value

Introduction

Labour shortages and rising costs of labour in the food and farming sector across Europe exhibit the fragility of agrifood systems. The EU agricultural sector is highly reliant on the ready availability of labour from both EU member countries and countries outside of the EU [1]. The nature of the coronavirus pandemic resulting in a sudden restriction of movement of seasonal workers is a prime example of how fragile European food systems are to shocks to the system. Agricultural robots not only present an opportunity to strengthen agrifood systems by addressing labour shortages, but also provide an opportunity to reduce CO_2 emissions [2] and soil compaction [3,4].

In this study, we adopt the definition of a field crop robot employed by Lowenberg-DeBoer, Huang, Grigoriadis, and Blackmore [5]: "a mobile, autonomous, decision making, mechatronic device that accomplishes crop production tasks (e.g. soil preparation, seeding, transplanting, weeding, pest control and harvesting) under human supervision, but without direct human labour".

A number of studies highlight that the adoption of digitalized technologies and robots in agriculture is not widespread due to a multitude of factors [6,7]. Lowenberg-DeBoer et al. [8] pinpoint on-site human supervision rules amongst some of the main challenges facing potential adoption in their study on regulatory issues that autonomous equipment has faced in other sectors (2022). Addressing human supervision, a recent study found that the economically optimal human supervision of robots lies between 13% to 85% across four modelled scenarios, suggesting a need for flexibility in regulations to make implementation of agricultural robots economically viable [9]. Farm size, education, and farmers' perceived economic barriers, were found to be critical variables

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https://doi.org/10.1016/j.atech.2023.100261
Received 30 December 2022; Received in revised form 22 May 2023; Accepted 27 May 2023
Available online 2 June 2023

Table 1
Basic data on TRC and AGR

Parameter	Unit	TRC	AGR
Investment	€	118,000	150,000
Depreciation per year	percent	15%	20%
Ownership years	years	5	5
Discount rate	%/year	4	4
Utilization capacity	hours / year	600	800
Fuel consumption	litre / hour	21.2	6
Labour price	€ / hour	35	35
Fuel price	€ /litre	1.5	1.5
Remote supervision	min / hour	–	5
Needed time for moves between fields	min / move	6	30
Internal/own labour use for maintenance	min/hour	10	10

affecting the adoption of smart farming technology in a study conducted by Caffaro and Cavallo [10].

Coinciding with considerable development within robotics and precision farming in the last 15 years, several economic feasibility studies have been published looking at conventional agricultural systems simulating scenarios where agricultural robots supplemented or replaced traditional machinery [11–14]. In a systematic review of agricultural automation and robotics, Lowenberg-DeBoer et al. [5] concluded that most of the economic studies focused on high value horticultural crops and to a lesser extent on commodity crops. In this study, we consider a mix of arable crops in a crop rotation system which to our knowledge has not been investigated much in previous studies on the economics of agricultural robots.

The main motivation for focusing on studying the supplementary use of agricultural robot alongside conventional tractor is that for the type of farming system considered (multi- crop rotation system), a robot is not yet capable of performing all operations that can be handled using a tractor. As such, tractor is anyway needed and robot adds to the farm's cropping capacity, operation efficiency and possibly net return. An important question regarding technology adoption decision is that how a technology under consideration fits into existing systems. However, existing literature is biased towards comparing sets of technologies and there is a clear lack of research providing in this research area to which this study is poised to contribute.

Drawing on a case study in the Netherlands, this study aims to develop a method to optimize the use of an AGR along with conventional tractor (TRC) in a traditional crop rotation system. Considerations have been given to important details about timing and operating constraints (e.g., working width, speed) for the target operations and crops during the cropping season different levels of labour and fuel costs, and relevant details specific to robot use (e.g., transport and monitoring time).

This study and pilot case in the Netherlands is part of the European project Robs4crops- a four-year project co-funded by the European Commission to accelerate the shift towards implementation of robotics and automation in European agriculture (see www.Robs4crops.eu).

Materials and methods

Case study description

To build upon existing literature on economic analyses in precision farming and autonomous robotic systems, a case study on a typical high-tech Dutch farm that implements both an agricultural robot and a conventional tractor is presented. The aim of this study is to propose a method to optimize the use of an autonomous robotic system. To assess this, a small-scale scenario consisting of single farm of 200 hectares, a tractor size of 120 kW (TRC) was chosen as it is typical for smallholder farms in the region of Oldambt, which is a heavy clay soil area in the Netherlands. The agricultural robot (AGR) selected is Robotti produced by Agrointelli of Denmark (www.agrointelli.com). It is an autonomous implement carrier with a traditional diesel-hydraulic setup, can mount conventional tools to perform various agricultural operations, and is camera equipped for implements. According to product technical specification [15], Robotti has 4-wheel drive, weighs 3150 kg, runs on two KUBOTA 55 kw diesel engines, has a customizable track width between 1.8 m and 3.65 m, and lift capacity of 750 kg. It runs with a max capacity speed of 5 km/h. (see www.agrointelli.com). According to Agrointelli, estimated price of Robotti 150D is about €150,000.

The operations chosen to demonstrate the optimal use of an AGR include seeding, tine weeding, inter-row hoeing, catch crop seeding, and spot spraying of crop protection agents. A multi-cropping crop rotation system of three high-value crops (sugar beets, pumpkins, and onions) and two grain crops (spring barley and winter wheat) is assumed. At current state of development, it is feasible to operate with the AGR in some operations and crop types but not all that a tractor can be used for. Operations not performed by the robot are handled by using tractor. According to opinions of expert farmers in the case study area, the AGR is capable of: sowing in all of the five crops, tine weeding in all crops except sugar beets, spot spraying in all crops except pumpkins, catch crop sowing after spring barley and winter wheat; hoeing in onions and sugar beets; harrowing in sugar beets, spring barley and winter wheat; and crosswise hoeing[1] in pumpkins.

Operations for which a robot is not suited for are performed by using conventional tractor. The scope of this study is limited to operations that can be handled by either a tractor or robot for the respective crops chosen for the case study.

Due to the size of the agricultural robot and accompanying implements, all operations with this robot take longer time to complete compared with a tractor. Investment costs and the expected operation hours per hectare for the tractor and AGR are based on real operating conditions conducted by farm contractors in The Netherlands using the Robotti.

In the present study, the reference case is an already high-tech farm already using technologies such as GPS, RTK, auto-steering, spot spraying, and precision application of inputs (e.g. fertilizer). In this case, the introduction/use of AGR is assumed not to change input application techniques, crop rotation strategies, yield and amount of other inputs apart from labour and fuel. Basic data on TRC and AGR is provided in Table 1.

Data

Data used in this study is compiled from KWIN[2] data provided from Wageningen University and Research in the Netherlands, Farmtal[3] from SEGES Denmark, product specifications from machinery manufacturers, literature, and expert opinions.

The reference tractor used in this study is a 4-wheel conventional tractor with a size of 120 kW. A 15% depreciation rate is used for the tractor because it is a matured technology, whereas a 20% depreciation rate is deemed relevant for the AGR. Table 2 presents width, operating speed and investment data for implements. Implement width, capacity, and investment price for the TRC.

All implements for the AGR are assumed to be 3 m wide. Not all of the 3 m implements are yet available for the AGR. Implement prices for TRC and AGR are based on market prices where available as well as expert estimates (November 2022). For each implement, capital costs are calculated with 12% depreciation per year, 8 years ownership, and 4% real interest rate. Relatively lower investment cost of AGR implements (shown in Table 2) is due to narrow widths. AGR autonomous

[1] It is translated from Dutch "vierkant verband schoffelen" referring to an operation where hoeing is done crosswise. It can also be referred to as square bandage hoeing. See for example, Mts Oosterhuis zaait bieten in ruit- en vierkant verband op de Groningse klei - akkerbouwbedrijf.nl.

[2] KWIN: the best book about Dutch greenhouse horticulture - WUR

[3] Farmtal Online | Software til landbruget | SEGES Innovation

driving speed is limited to a maximum of 5 km/hour. This is a reasonable limit under current regulation and for safety concerns considering the state of technology maturity.

Assumptions

In the model, the following working assumptions have been made:

Tractor and AGR use their own implements without sharing between them. On a farm using both TRC and AGR, it is sensible for each to have implements ready so that they can be used complementarily when and where needed.

At current state of technology (and in the coming few years), a person can remotely supervise only one robot for farming operations. Possibility of simultaneously monitoring 'fleets of robots' would help reduce per unit cost of monitoring. However, practicality of fleet monitoring in the case of field crop operations is yet to be realized, at least in the case study area.

Introduction/use of an AGR in an already high-tech precision farming system does not change a farmer's input application and crop rotation strategies, nor does it change crop yield and quality. In reality, farmers adjust their cropping systems in response to changes in mechanization. Given that the focus of this study is on an already high-tech farm implementing both tractor and robot systems, those adjustments in farming system would have comparable implication for the AGR and TRC cases. Some of the adjustments in fact may need longer time than the 5 years optimization timeline considered in this study.

Operating speed of implements does not change with tractor size but implement width needs to be adapted to tractor size.

The farmer owns TRC, AGR and the various implements. Unused capacity can be shared with a neighbour enabling non-integer optimization in the model. For example, if the optimization model suggests the use of 0.6 units of AGR, it means that the cost incorporated in the optimization is only the share associated with the 0.6 unit but not the entire cost for a one unit of AGR. In reality, limited time windows for field operations potentially affect the practicality of machine sharing. A multi-cropping crop-rotation system as in this case study offers better flexibility for machine sharing because of different operation timing across the different crops added to the possibility of different farmers having differing crop mixes. Transaction costs associated with coordinating machinery sharing could be minimized through networks such as farmers' cooperatives.

Definition of working assumptions and choice of parameter values were guided by learnings from rounds of discussions with a farming contractor working in the case study area (using both conventional tractor and Robotti) as well as a representative from robot manufacturer AgroIntelli.

Scenarios

Remote supervision capacity (RSC) is defined, in this context, as the number of available hours per week that a farmer potentially has to supervise an AGR. Assuming a 40-hour normal business week for a farming enterprise, we set the lower limit of RSC to 40 h/week. The lower limit 40-hours is set based on an 8-hours business day for 5 days in a week. Of course, peak seasons demand longer working hours (as was shown for the case of May month in Table 7 and section 3.3). This has been relaxed under scenarios #4-#10 shown in Table 3. It is worthy of note here that outside of normal business hours, hourly rates for labour to supervise a robot can be higher than average labour price. Moreover, with possibilities to remotely control one more robot, the remote

Table 2
Implement width, operation speed and investments.

Implement for operation	Max width *(m)	Width for TRC (m)	Speed TRC (km/h)	Speed AGR (km/h)	Implement investment TRC (€1000)	Implement investment AGR (€1000)
Precision seeding	12	6	5	4.5	45	15.91
Seeding cereals	12	6	5	4.5	35	12.37
Tine weeding	15	9	4.4	5	25	2.78
Hoeing	9	4.5	5.6	5	35	16.87
Spot spraying	12	6	3.3	3	105	56.27
Catch crop seeding	9	4.5	6.7	5	10	4.82
Crosswise hoeing	9	4.5	4.4	4	35	15.56

*Max width refers to the maximum available working width for conventional tractors for the respective field operations in the case study area.

Table 3
Scenario definition.

SN	Scenario description	Supervision time (ST) (minute/hour)	RSC (hours/ week)	Labour price (Lp) (€/hour)	Fuel price (Fp), (€/L)	Tractor size (Tz), (kw)	AGR Implement price
#1	Basic scenario (minimal monitoring)	5	40	35	1,5	120	as in Table 2
#2	Medium monitoring under limited supervision capacity	15	40	35	1,5	120	>>
#3	High monitoring under limited supervision capacity	30	40	35	1,5	120	>>
#4	Minimal monitoring under unlimited supervision capacity	5	unlimited	35	1,5	120	>>
#5	Medium monitoring under unlimited supervision capacity	15	unlimited	35	1,5	120	>>
#6	High monitoring under unlimited supervision capacity	30	unlimited	35	1,5	120	>>
#7	Minimal monitoring, unlimited supervision capacity, high fuel price, adjusted tractor size	5	unlimited	35	2	115	>>
#8	Minimal monitoring, unlimited supervision capacity, high labour price, adjusted tractor size	5	unlimited	45	1,5	160	>>
#9	Minimal monitoring, unlimited supervision capacity, high labour & fuel price, adjusted tractor size	5	unlimited	45	2	155	>>
#10	Minimal monitoring, unlimited supervision capacity, AGR implement price as TRC implement	5	unlimited	35	2	120	Same as TRC implement

SN= scenario number.
Unlimited RSC implies theoretically infinite hours of RSC per week (>400 used in the analysis). This is equivalent to 'negligible supervision cost'.
Scenario #10 is the same as scenario #4 except for AGR implement price.

Table 4
Number of field operations per week by crop type.

Month/week number/ Operation	February 3	March 2	March 4	April 1	April 2	April 3	April 4	May 1	May 2	May 3	May 4	June 1	June 2	June 3	June 4	September 1	September 4	October 2	October 4	Crop
Precision seeding					1															Onions
Tine weeding						1	1													
Hoeing								1	0.5	0.5										
Spot spraying											1									
Catch crop seeding																	1			
Precision seeding										1										Pumpkins
Tine weeding											1									
Crosswise hoeing												2	2	2	2					
Catch crop seeding																	1			
Precision seeding			1																	Sugar Beets
Hoeing					1		1		1		1									
Spot spraying								1		1										
Catch crop seeding																			1	
Seeding cereals																		1		Winter wheat
Tine weeding	1	1		1				1											1	
Spot spraying						1														
Catch crop seeding																1				
Seeding cereals		1																		Spring Barley
Tine weeding			1			1			1											
Spot spraying								1												
Catch crop seeding																1				

supervision time limit increases by 40 h. For example, if a person can remotely control 3 robots at a time (while possibly doing something else on the side), the theoretical available supervision time is relaxed to 120 h.

To account for possibilities of having an AGR operate day and night, and/or a person supervising several AGRs at a time, we also considered a case where supervision capacity is not a limiting factor. Table 3 gives an overview of the basic scenario and 9 other scenarios with varying combinations of time for remote supervision, labour and fuel cost, implement price and tractor size.

Optimization procedure

To compare the different operational scenarios and to assess optimal combinations of AGR and TRC to use under different conditions and assumptions, four essential steps are considered. The first step is to setup a calendar for the timing of various operations for different crops. Step two concerns with cost estimation for each operation for TRC and AGR. A ranking of possible combinations is then performed according to the estimated hourly cost of operation. The fourth step is execution of the identified least cost alternative. Each of the steps are elaborated in the subsections that follow.

Step I: Setting up operation calendar

The study considers a multi-cropping system involving five crops: onion, pumpkin, sugar beet, winter wheat and spring barley. These crops are assigned different area share: onion (10%), pumpkin (5%), sugar beet (20%), winter wheat (30%) and spring barley (35%). A single farm of 200 ha with an average field size of 10 ha is used for the analysis. Field operations considered feasible with AGR in one or more of the crops considered are seeding, tine weeding, hoeing, spot spraying and catch crop seeding. In the case study area, the time window for these field operations runs from the third week of February until end of October. A weekly operation plan has been set up as displayed in Table 4 (the numbers indicate the number of times an operation is performed per a specific week for the respective crops). For example, hoeing in onions is done in May (entire onion field in the first and fourth weeks, half in the second week and the remaining half in the third week). Crosswise

Table 5
AGR utilization (% of farm area) and labour use by type of field operation and crop: basic scenario.

Month/week number/ Operation	February 3	March 2	March 4	April 1	April 2	April 3	April 4	May 1	May 2	May 3	May 4	June 1	June 2	June 3	June 4	September 1	September 4	October 2	October 4	Crop
Precision seeding					90															Onions
Tine weeding						0	100													
Hoeing								100	100	100										
Spot spraying											60									
Catch crop seeding																	100			
Precision seeding										0										Pumpkins
Tine weeding											0									
Crosswise hoeing												100	100	100	100					
Catch crop seeding																	100			
Precision seeding			100																	Sugar Beets
Hoeing					100		100		100		100									
Spot spraying								60		75										
Catch crop seeding																			100	
Seeding Cereals																		90		Winter wheat
Tine weeding	100	0		100				0											33	
Spot spraying						60														
Catch crop seeding																100				
Seeding cereals		77																		Spring Barley
Tine weeding			22			0			14											
Spot spraying								0												
Catch crop seeding																0				

Table 6
Optimal number of TRC and AGR units, MAV of AGR and breakeven farm size for one AGR under different scenarios.

Scenario number	TRC REF (units)	TRC + AGR (units)	MAV AGR (€)	*Breakeven farm size for TRC REF (ha)*	*Breakeven* farm size for AGR under TRC+AGR (ha)
#1	0.85*	0.32 + 0.81	133,748	235	247
#2	0.85	0.4 + 0.65	115,192	235	306
#3	0.85	0.65 + 0.25	134,936	235	800
#4	0.85	0 + 1.39	115,477	235	144
#5	0.85	0.23 + 0.92	98,942	235	217
#6	0.85	0.65 + 0.25	134,936	235	800
#7	0.87	0 + 1.39	124,100	230	144
#8	0.71	0 + 1.39	121,378	282	144
#9	0.72	0 + 1.39	131,973	278	144
#10	0.85	0 + 1.39	−48	235	144

*Machinery unit of 0.85 means for the reference farm of 200 ha, only 85% of machinery capacity is needed to accomplish the target operations for the considered crops during one season. The remaining capacity could be used somewhere else.

Table 7
Field operation hours per year and during peak month (May) by type of operation.

Operation	Field operation (ha /year)			Field operation (hours /year)			May field operation (hours/week)		
	REF	TRC	AGR	REF	TRC	AGR	REF	TRC	AGR
Precision seeding	70	12	58	23	4	43	0.8	0.8	0
Seeding cereals	130	22	108	43	7	80	0	0	0
Tine weeding	560	374	186	140	94	124	8.8	8.1	1.7
Hoeing	200	0	200	80	0	133	12	0	20
Spot spraying	230	128	102	115	64	113	21.3	13	18.3
Catch crop seeding	200	70	130	67	23	87	0	0	0
Crosswise hoeing	80	0	80	40	0	67	0	0	0
Total	1470	606	864	508	192	647	42.8	22	40

REF=reference case with only tractor.

Table 8
Annual and peak month labour use by scenario.

Scenario	Labour hours AGR+TRC	Labour hours TRC REF	Weekly AGR hours in May	Weekly labour use in May	Share of labour in May	Share of AGR use in May
#1	516	657	40	45	25%	35%
#2	611	657	38	51	29%	33%
#3	669	657	20	56	40%	34%
#4	458	657	92	37	33%	33%
#5	606	657	69	51	37%	33%
#6	669	657	20	56	40%	34%
#7	458	674	92	37	33%	33%
#8	458	550	92	37	33%	33%
#9	458	561	92	37	33%	33%
#10	458	657	92	37	33%	33%

hoeing of pumpkins is done twice a week throughout June.

In reality, investments to achieve 'optimal timing in view of yield maximization' may not necessarily translate in to 'maximum net return'. The crop calendar in Table 4 is an operation schedule indicative of what is common practice in the study area. In fact, farmers do adjust their field operation depending on circumstances, be it resource constraint or weather conditions. In part, this sub-optimality phenomenon gives room for the practicality of machine sharing. For example, instead of buying a machine themselves, some farmers may prefer to share-in a machine and seed a bit earlier or later than what they would ideally do.

Step II: Cost estimation

Once the operation plan has been set out as in Table 4, the next step in the optimizationm exercise is to estimate costs of operating with TRC and AGR.

In this case study, total cost of operating with TRC includes discounted capital cost of TRC and its implements, operating labour cost and fuel cost. Operating labour cost includes cost of labour to drive the tractor during field operation, maintain (both TRC and its implements) and move the tractor from field to field. Similarly, total cost of operating with AGR includes discounted capital cost of AGR and implement, operating labour cost and fuel cost. In the case of AGR, estimated labour cost to remotely supervise AGR is included instead of driving during operation. Moving between fields may take longer time than does moving TRC if robot needs to be loaded/unloaded on and from a trailer. In cases of adjacent fields, AGR transport time could be reduced making the robot walk to the next field via remote control with no need to load and unload it on a trailer. For simplicity, we used average time to move robot between fields.

Present value (PV) calculations are done for a five-year investment horizon using the farmer's real interest rate as a discount rate (4%), at depreciation rate of 15% for TRC and 20% for AGR using standard NPV formula. To express discounted values over the investment horizon in yearly terms, an annuity factor has been used. Break-even investment for the AGR also referred to as Maximum Acquisition Value (MAV) is defined as the amount of investment for a unit of AGR that provides the same net benefit as the TRC reference scenario (REF). In the context of this study, net benefit is approximated by fuel, labour, AGR and implement cost.

Step III: Ranking

The decision of what to use AGR and TRC for and to what extent it is done for every individual week. In this study, net benefit of AGR is approximated by the difference in total cost of operation in the TRC

Fig. 1. Reduction in TRC hours, labour hours and fuel consumption due to AGR.

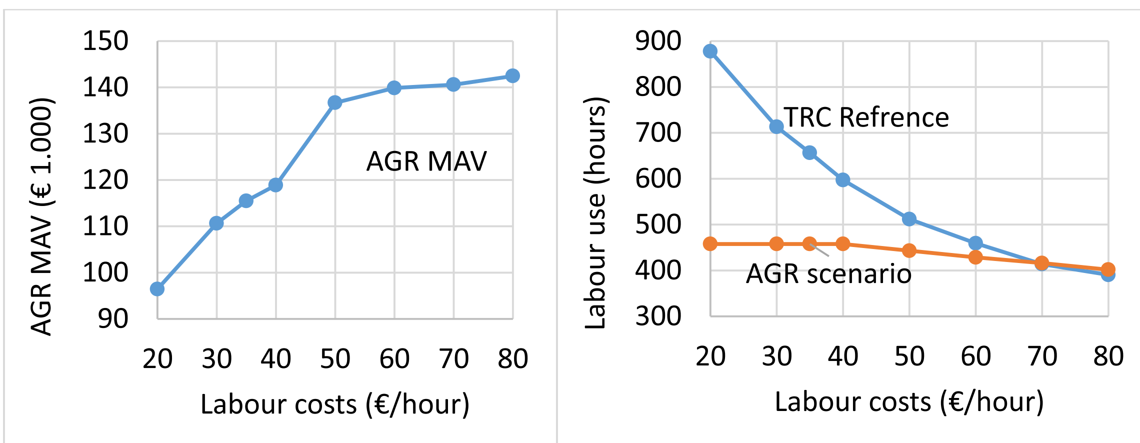

Fig. 2. Change in use of AGR, TRC and labour due to changing labour costs.

Table A1
Cost estimates for TRC and AGR under basic scenario.

Cost item	Unit	TRC	AGR
Depreciation	€ / hour	28.1	30.8
Maintenance, external	€ / hour	7.4	5.8
Maintenance, own labour[1]	€/hour	5.6	5.6
Fuel cost	€ / hour	31.8	9
Variable cost	€ / hour	45	20.5
Total operating cost, excluding labour	€/hour	73.1	51.2

[1] Own (internal) labour time for maintenance is estimated 10 min/hour both in the case of AGR and TRC.

reference case and the one with AGR. Under the assumptions made (same yield and input cost), the difference in net benefit equals the difference in cost of the two systems. Hence, the focus on cost is a valid approach in this context.

AGR net benefit= Total cost of operating (TRC REF) - Total cost of operating (AGR)

Total cost includes fuel, labour (to operate the TRC, supervise the AGR), discounted machinery capital cost, and machinery maintenance cost (external and internal).

For each operation and each crop, the least cost alternative (in terms of total operation cost per hectare) is chosen.[4] Though hourly cost of operation in a crop or more is lower for AGR case, AGR cannot be used for lack of capacity to monitor it. For example, on a farm with only one or two workers (which is said to be typical of a farm of about 200 ha in the case study area), 'time available for robot monitoring' is most likely very limited. Even when operation requirements allow to work for longer hours per day with AGR, hourly labour price outside of normal business hours could be much higher reducing relative attractiveness of AGR use. Therefore, when available RSC is used up, tractor operations takeover anyway. In this regard, how many robot units a person can monitor at a time plays a critical role.

The non-integer optimization allows combined use of AGR and TRC. Some operations may be performed by either or a combination of TRC and AGR.

Table A2
Implement capacity and tariff.

Operation/implement	Implement capacity (ha/hour)		Implement tariff (€ / hour)	
	TRC optimal	AGR 3m	TRC	AGR
Precision seeding	3	1.4	41.1	14.5
Seeding cereals	3	1.4	31.9	11.3
Tine weeding	4	1.5	22.8	2.5
Hoeing	2.5	1.5	31.9	15.4
Spot spraying	2	0.9	95.8	51.3
Catch crop seeding	3	1.5	9.1	4.4
Crosswise hoeing	2	1.2	31.9	14.2

Implement capacity is derived from implement width and speed data presented in Table 2.

[4] To take care of instances of equal values for TRC and AGR, a random approximation has been added to result in a definite rank.

Table A3
Labour hours by week under reference and AGR+TRC cases.

Month	February	March		April				May				June				September		October	
Week of the month	3	2	4	1	2	3	4	1	2	3	4	1	2	3	4	1	4	2	4
Labour hours (TRC REF)	20	50	40	20	29	68	27	100	49	35	37	13	13	13	13	56	13	26	37
Labour hours (TRC + AGR)	17	38	32	17	17	51	17	70	34	23	23	7	7	7	7	37	8	18	28
Reduction due to AGR (%)	14	23	20	14	40	24	38	30	31	34	38	47	47	47	47	35	35	29	24

Table A4
Reduction in use of tractor, labour, fuel, and total cost with optimal use of AGR.

Scenario	ST	RSC	Lp	Fp	TRC hours	Labour hours	Fuel consumption	PV total cost*
#1	5	40	35	1.5	62%	21%	26%	−3%
#2	15	40	35	1.5	53%	7%	24%	9%
#3	30	40	35	1.5	24%	−2%	12%	4%
#4	5	unlimited	35	1.5	100%	30%	38%	19%
#5	15	unlimited	35	1.5	72%	8%	32%	9%
#6	30	unlimited	35	1.5	24%	−2%	12%	4%
#7	5	unlimited	35	2	100%	32%	38%	20%
#8	5	unlimited	45	1.5	100%	17%	42%	19%
#9	5	unlimited	45	2	100%	18%	42%	21%
#10	5	unlimited	35	2	100%	30%	38%	−15%

* Discounted total cost over 5 years.

Step IV: Execution

For each crop and operation type, the optimization model presents the farmer with a decision support on how many units of AGR and/or TRC to use. It is then up to the decision maker to execute the field operations based on the decision support provided by the optimization model.

The study adopts a post-investment optimization approach in the sense that all the implements, TRC and AGR are assumed to have been owned by the farmer. Hence, the model is not such a strategic decision support tool to decide whether to invest in AGR or not; rather it focuses on how optimally to use it once it has been acquired.

Results

Optimal use of AGR under basic scenario

Optimal use of the AGR is estimated with 40 h per week remote supervision capacity. When all the 40 h are used, the TRC operations take over. This planning takes place for each individual week. For that reason, some operations like hoeing in onions and sugar beets, for example, sometimes are done only by AGR, sometimes only with TRC and other times by a combination of TRC and AGR.

Table 5 shows the optimal utilization of the AGR for the various operations and crops by week of operation during the considered operational months. The entries marked with green colour represent 100% use of the AGR; those in yellow represent combined use of AGR with TRC; and the red coloured entries denote 0% use of AGR (100% use of TRC). For example, optimal use of the AGR requires that it is used for 90% of the farm area for precision seeding of onions in the second week of April, complementing the rest with conventional tractor. It is optimal for the farmer to use only the AGR (100%) for tine weeding (in the 4th week of April), hoeing (during the first three weeks of May) and catch crop seeding (last week of September) in onions. In the case of pumpkins, the model suggests 100% use of AGR for crosswise hoeing and catch crop seeding, and no use for seeding and tine weeding. Under the basic scenario, labour use is lower in the TRC+AGR case (for all operations and crops) compared to the reference TRC case.

Break-even investment for the AGR also referred to as AGR Maximum Acquisition Value (MAV) is defined as the price of the AGR that provides the same net profit (in the context of this study, net benefit is approximated by fuel, labour, AGR and implement cost) as the current use of tractors (TRC reference). MAV is the break-even investment price of AGR. The break-even value expresses the AGR investment cost that will make the AGR scenario as profitable as the TRC reference scenario (TRC REF) on a 200-hectare farm. Table 6 presents optimal number of TRC and/or AGR units for a farm of 200 ha, breakeven investment and farm size for a unit of AGR under the different scenarios.

Purchase prices for the AGR and its implements are important determinants for the profitability and use of the AGR. The calculations for the BE farm size, have been based on an estimated €150,000 purchase price for the AGR and it has been assumed that implements adjusted for the AGR can be acquired at prices listed in Table 2.

As can be seen from Table 6, breakeven farm size for one AGR under *basic* scenario is 247 ha. Under scenarios #3 and #6, the break-even farm size is as high as 800 ha. This is because the high monitoring requirement makes the AGR attractive to use in only a few operations requiring only a quarter of robot units to perform those operations on the case farm of 200 ha.

If implement costs, however, are the same as the reference TRC, the optimal use of the AGR in most cases will be limited to hoeing, crosswise hoeing and catch crop seeding.[5] The MVP AGR close to zero (−48 €) under scenario #10 implies that buying AGR at the estimated price of 150,000 € is not a justifiable decision if implement prices are as high as TRC implement prices listed in Table 2. However, once investment in AGR had been made, the optimization model suggests the use of 1.4 units of AGR (and no TRC) for its labour and fuel saving advantages. Under scenarios #4 and #7 through #10, it is optimal to use AGR for all operations and crops considered.

Field operation area coverage and operation hours under basic scenario

As can be seen from Table 7, total field operation hours increased from 508 with the TRC reference to 839 (192 h with the TRC plus 647 h with the AGR). At the same time, labour hours are reduced from 657 to 516 h per year. For the peak month (May), labour use decreases from 55 h per week in the TRC REF to 45 h per week in the TRC+AGR scenario. Due to the limited RSC, the AGR is allocated to hoeing and some spot spraying and tine weeding.

Owing to the narrow width and slow operating speed of AGR, total field operation hours for all crops combined are 65% higher in the TRC

[5] Implement width with increasing TRC size (kW) is estimated with a 0.6-0.7 power function and an assumed unchanged operation speed.

+ AGR case (increased from 508 with the TRC REF to 839 (192 h with TRC + 647 h with the AGR). In the case of seeding, total operation hours doubled whereas a relatively lower increase is observed for spot spraying and tine weeding (54% and 55%, respectively).

Labour use per year and during peak month under different scenarios

Table 8 presents annual and peak-month labour use under the different scenarios for reference case of only tractor and that of TRC+AGR.

The month May accounts for more than a third of yearly labour and AGR hours ranging respectively between 25 and 40% and 33–36% under the different scenarios (see Table 8).

Changes due to AGR under different scenarios

Under the basic scenario (#1), labour hours are reduced from 657 to 516 h per year. For the busy month (May), labour use is reduced from 55 h per week with the TRC reference to 45 h per week in the TRC+AGR scenario. With high requirements for supervision (30 min of robot supervision per every hour of operation under scenarios #3 and #6), the AGR+TRC case resulted in a higher total labour hours as compared to the TRC reference case.

Generally, all other results under scenarios #3 and #6 are the same exemplifying the decisive role of time needed to do monitoring of robots. The theoretically ‘unlimited’ remote supervision capacity under scenario #6 does not appear to help in the case of high requirements for monitoring. This changes with possibilities of remotely monitoring multiple robots at a time. For example, keeping other parameters as in the basic scenario, if a person can monitor 4 robots at a time, all operations (except for part of tine weeding in winter wheat) shall be performed with AGR. With monitoring of 5 robots, it is optimal to perform all the considered operations with AGR.

Fig. 1 shows the percentage reduction in TRC operation hours, aggregate labour hours and fuel consumption (for all crops and operations combined) in the TRC+AGR case relative to the reference case of using only tractor.

As shown in Table A 4 in the appendix, under the basic scenario, operation hours with TRC, fuel consumption and aggregate labour use are 62%, 26% and 21% respectively lower in the TRC+AGR case relative to TRC-only reference case.

Fig. 2 depicts the relationship between labour cost and MAV of AGR as well as the use of labour, keeping all other scenario parameters as in the *basic* scenario.

The left panel in Fig. 2 shows the change in MAV of AGR as a function of hourly labour costs. At a labour price of about 80 €/hour, MAV is closer to the estimated purchase price of 150,000 €/unit of AGR implying that the investment cost for AGR is justified in cases of higher labour prices. For example, at a labour cost of 30 €/hour, the maximum reasonable price for a farmer to pay for a unit of AGR is about 110,000 €. The panel to the right shows that with increasing labour cost, labour hours decline at a higher rate in the reference TRC-only scenario. Whereas, in the case of AGR+TRC, total labour hours are less sensitive to labour price most likely due to the effect of time needed to monitor the robot and move it from field to field.

Under scenarios #4 and #7 through #10, 0 TRC and 1.4 AGR is an optimal application. With increasing labour costs less AGR (reduced from 1.4 to 0.8 units), but more, and bigger, TRC are applied (increasing from 0.0 to 0.2 units), whereas less AGR are applied (decreasing form 1.4 to 0.75 units). The labour use is slightly decreasing (from 460 to 400 h), the 5 year total costs are increasing (from €350,000 to €450,000) and the AGR maximal acquisition value (MAV) is increasing (from € 98,000 to €141,000).

With labour costs from 50 €/hour and upwards there are receding difference between the TRC REF and the TRC+AGR cases in terms of labour hours and total costs. There are however huge differences for labour costs below 50 €/hour. There is no need for a TRC but 1.4 units of AGR and the labour use is significantly reduced. The total costs are however higher with the AGR and as a consequence the AGR MAV is also significantly below the estimated €150,000 purchase price.

Discussion and perspectives

Under the cases and scenarios considered in this study, optimal utilization of an AGR brings sizable gains in terms of reduced labour use. For example, under the basic scenario, optimal use of AGR alongside TRC reduced aggregate labour use by about 30%. This is in support of farmers' expectations about AGRs to help reduce labour demand [16]. However, the labour saving advantage vanishes with increased monitoring requirement. For example, in case of 50% monitoring requirement (i.e., 30 min per hour of field operation), aggregate labour use is higher in the AGR+TRC scenario compared to the reference case (TRC REF). Further maturity in the AGR technology to reliably handle agricultural operations without compromising safety (of crops, humans, animals and built environment) could potentially lower monitoring needs and hence offer considerable labour saving to farmers. As noted in Maritan, Lowenberg-DeBoer, Behrendt, & Franklin [9], flexibility in regulatory monitoring standards is crucial in this regard. This also calls for comparable developments and clarity in regulatory frameworks concerning robot monitoring.

Moreover, the use of AGR brings about significant reduction in yearly tractor hours compared to the reference case of using only tractor. However, due to low width of AGR and slow operation speed, field operation hours are higher in the AGR+TRC case. As AGRs can ideally work outside of conventional business hours, longer operation hours may not be much of a concern. Possibilities of having a fleet of robots in operation under remote supervision [17], would help in minimizing duration of field operations. At the same time, this would present opportunities to minimize per unit monitoring cost.

Corresponding to reduction in TRC operation hours, significant reduction in fuel consumption. Besides, cost saving for the farmer, this is a promising indication towards the potential of AGRs to help reduce GHG emission in line with Gonzalez-de-Soto, Emmi, Garcia, & Gonzalez-de-Santos [2].

In all the scenarios considered, MAV of AGR is lower than its estimated purchase price of €150,000 per unit. Especially in case of high price of AGR implements (see Table 6), buying AGR is not justifiable as evidenced by the negative AGR MAV value. However, in instances of labour unavailability let alone high price, the AGR could be the only solution to reduce the farmers working hours (e.g., during peak seasons) and meet constraints in getting operations done according to agronomical optimal timing requirements. As reported in Tamirat *et.al.* [16], high investment cost is on top of farmers' concerns related to farming robots. Sharing arrangements and/or affordable contractual services would be part of the portfolio of efforts to make AGRs accessible to farmers. Moreover, manufacturers need to carefully consider designing AGRs in a way that they can handle wider implements.

While the framework can be adapted to other setups (crops, operations, machinery sizes, input price, investment, etc.), the quantitative results presented are specific to the context of the study described in the *materials and methods* section. One example to illustrate the specificity can be the type of soil on the case farm. With other soil types than the considered heavy clay soil from the Dutch Oldambt district, results may differ, but not necessarily in favour of the AGR. On more sandy soils, the ha/hour speed of tractor operations may increase relatively more than the AGR operations which are limited by the 3 m width and 5 km/hour maximum driving speed (resulting in a maximum of 1.5 ha per hour operation speed). On the other hand, considerations of soil compaction from using heavy machinery (especially so in clay soils during the wet seasons) could favour the use of lighter AGRs despite high investment cost. As reflected in Spykman et al. [18], larger farms may prefer large autonomous tractors with primary consideration of financial considerations compared to small-scale or organic farmers that tend to consider environmental benefits relatively more.

From research perspective, the following appear to be worth considering to further expand the model:

- Incorporate other cost components in relation to AGR, e.g., geo-fencing
- Include other scenario parameters: e.g., time needed to move AGR from field to field
- Other potential benefits due to AGR, e.g., further precision in input application, reduced soil compaction, reduced exposure to tractor vibration, reduced chemical emission, etc.
- Possibility of remotely monitoring several AGS at a time
- Alternative modes of access, e.g., contracting

Relaxing some of the simplifying assumptions would also be an important step forward. For example, no change in input application techniques or crop rotation strategies has been incorporated in the present study. In reality, investing in AGR could increase the overall cropping capacity of the farm thereby enabling growing more of labour demanding high value crops by substituting labour intensive tractor operations with robot operations. Intensified crop rotation may in turn increase income and demand for fuel, fertilizers and pesticides.

Given that 3 m implements are not yet available in the market, it was not possible to find any reference cost data for AGR implement; and we have to rely on optimistic best guesses that may affect the magnitude of estimated changes reported in this study. Despite this, the study presents an adaptable framework, which is an important contribution to the not yet well-investigated research area of how to best integrate AGRs with existing tractor-operation systems.

Even though the focus of this study is on presenting a model for optimal utilization of an AGR in a tractor-robot setting, the MAV calculations shed important insights to strategic decisions of whether or not to invest in AGR.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

Acknowledgement

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 101016807.

Appendices

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