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RESEARCH ARTICLE

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Performance of machinery in potato production in one growing season

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Abstract

Statistics on the machinery performance are essential for farm managers to make better decisions. In this paper, the performance of all machineries in five sequential operations, namely bed forming, stone separation, planting, spraying and harvesting in the potato production system, were investigated during one growing season. In order to analyse and decompose the recorded GPS data into various time and distance elements for estimation of the machinery performance, an automatic GPS analysis tool was developed. The field efficiency and field capacity were estimated for each operation. Specifically, the measured average field efficiency was 71.3% for bed forming, 68.5% for stone separation, 40.3% for planting, 69.7% for spraying, and 67.4% for harvesting. The measured average field capacities were 1.46 ha/h, 0.53 ha/h, 0.47 ha/h, 10.21 ha/h, 0.51 ha/h, for the bed forming, stone separation, planting, spraying, and harvesting operations, respectively. These results deviate from the corresponding estimations calculated based on norm data from the American Society of Agricultural and Biological Engineers (ASABE). The deviations indicate that norms provided by ASABE cannot be used directly for the prediction of performance of the machinery used in this work. Moreover, the measured data of bed forming and stone separation could be used as supplementary data for the ASABE which does not provide performance norms for these two operations. The gained results can help farm managers to make better management and operational decisions that result in potential improvement in productivity and profitability as well as in potential environmental benefits.

Additional key words: GPS data analysis; operation management; machinery management; field efficiency; field capacity; *Solanum tuberosum* L.

Abbreviations used: ASABE (American Society of Agricultural and Biological Engineers); EFC (effective field capacity); FE (field efficiency); GPS (Global Positioning System); MBR (minimal bounding rectangle); MIO (material input operation); MNO (material neutral operation); MOO (material output operation); SU (service unit)

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Introduction

Agricultural machinery inputs are the major capital investment, which can be as high as 25% of the total cost of crop production (Adamchuk *et al.*, 2011). Efficient use of agricultural machinery in field operations becomes very important to reduce the cost of the operations. Therefore, knowledge about the performance of the machinery in field operations is a requirement for better operation management and planning.

The field efficiency (FE) and capacity are two important measures for estimation of machinery performance, which can be estimated by time-motion studies. Traditional methods have utilized stopwatches and meters to collect field operation data for machinery performance evaluation. For example, Renoll (1981), Sørensen & Nielsen (2005) and Sørensen & Møller (2006) used stop watches and clipboard to evaluate the field machinery performance. However, these recording methods are time demanding and laborious for a technician to measure the data manually during the operation. Alternatively, in the last decade, the extensive use of Global Positioning System (GPS) equipment has provided farm managers a new promising method to monitor and evaluate the field machinery performance. GPS equipment has been used to estimate performance of various machineries in various agricultural field operations, *e.g*. mower, rake and baler in cotton residue collection (Ntogkoulis *et al.*, 2014); combine harvesters in corn, soybean and wheat harvesting (Taylor *et al.*, 2002); slurry applicator in manure spreading (Bochtis *et al.*, 2010); planter in corn and soybean planting (Grisso *et al.*, 2002); and harvester of olive (Castillo-Ruiz *et al.*, 2015) and of forage corn for silage (Harrigan, 2003). In addition, analysis algorithms have been developed to automatically extract and analyse the GPS data. Adamchuk *et al.* (2011) developed an algorithm to evaluate the spatial variability of the machinery performance. The processed spatial information can be used by famers to optimize the traffic pattern. Jensen & Bochtis (2013) developed an algorithmic method for automatic recognition of machine operation modes for cooperating machines (*i.e.* combines and transport units in grain harvesting) based on analysing recorded GPS trajectories.

To the authors' knowledge, all of the current studies are focused on monitoring a single machine or multiple machines that are involved in a single field operation, not on all the machines in the complete set of field operations in one crop production system. In this paper, the potato production has been chosen as the case study. There are five main sequential field operations in potato production: Bed forming, stone separation, planting, spraying and harvesting. The bed forming operation is decisive, since it determines the bed layout, the driving direction and the wheel tracks for the entire growing season. Since the machines cannot turn inside the bed area and they must follow the wheel tracks between the beds the bed forming also influences the working width of each machine, which must be one or multiple bed widths. Consequently, investigating the performance of all machineries in potato production is a key step to make an optimal operation planning.

In addition, a large volume of GPS data is collected during the sequential field operations in one growing season, which is time consuming to analyse manually. Hence there is need to develop an automatic GPS analysis tool for decomposing GPS recordings from a complete set of field operations into time and distance elements in various activities, such as turning in the headland area, transporting, etc. Specifically, the objectives of this work are as follows: (i) to develop an analysis tool to process the recorded data in order to reveal the time contribution of different task elements of each operation; (ii) to analyse the field capacity and efficiency of the different machinery involved in the related field operations; (iii) to compare the measured FE and capacity with computed FE and capacity based on ASABE data.

Material and methods

Description of operations

The five main sequential field operations involved in potato (*Solanum tuberosum* L.) production are explained in details in the following:

1. Bed formation: Setting up perfectly formed beds is the first step towards successful establishment of a potato crop. The bed former uses shaped metal plates to lift up the soil and form it into one to more beds. This step is decisive, since the wheel tracks and the bed width are determined for all subsequent field operations of the season (Fig. 1a).
2. Stone separation: This operation is also a part of the seedbed preparation in stony and cloddy soils which can provide ideal growing conditions for fast emergence of the potatoes and reduction of the picking cost in the harvesting. A stone separator uses a digging share and separating web through which the fine soil falls into the bed while the oversize stones and clods are transferred laterally through a cross-conveyor to an adjacent furrow between already formed beds where separation is not performed. The conveyor can be adjusted either to the right or left when the tractor is at the end of the current bed. In successive operations the machine's tires run on the rows of the processed stones and clods to bury them between alternate beds (Fig. 1b).
3. Planting: Potato planting starts immediately after the stone separation, normally by the use of automated planters. The planter is attached behind a tractor with the seed potatoes in a container, called the hopper. Special cups lift the seed potatoes from the hopper and place them with accuracy distance into the beds. The depth of sowing is about 5-10 cm and the distance between potato tubers along the rows are about 20-40 cm. Due to capacity constraints the hopper needs to be refilled occasionally. This is done by driving to the headland area where one or more reloading units are located, refill the hopper and return to the location of the field where the hopper ran empty. The time spent for reloading is part of the non-working time (Fig. 1c).
4. Spraying: Spraying with herbicides, pesticides, fungicides etc. are usually performed around 10 times during the entire season (Fig. 1d).
5. Harvesting: The most common harvest method is using a potato harvester with two or three rows diggers, depending on the bed type, which can dig out the potatoes from the bed. Soil and crop are transferred onto a series of webs where the loose

Figure 1. The involved field operations in potato production: (a) bed forming; (b) stone separation; (c) planting; (d) spraying (photo source: gopixpic); (e) harvesting**.**

soil is screened out. The potatoes are conveyed to a separation unit at the back part of the harvester. The potatoes then go on to a side elevator and into a trailer or bin located somewhere in the field (Fig. 1e).

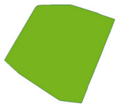
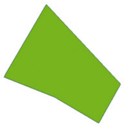
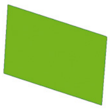
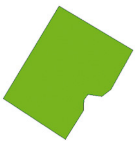
Experimental field operations

Site description. The experiment was designed to record GPS data of the activities of all the machineries involved in the sequential in-field operations of the potato production in ten fields in Lolland, Denmark, from May to December 2014. Table 1 summarizes the information about the study fields' shape, location and area.

Machinery and GPS recording equipment. The considered potato planting system consisted of 2.25 m wide beds which was the basic module width. Each bed consists of three rows. For each field crossing the bed former can produce two beds (one complete and two half beds). The stone separator, the harvester and the planter can only process one bed, while the sprayer can process 11 beds per crossing. Hence, the operating width *w* was 4.50 m for the bed former, 2.25 m for the stone separator, the harvester and the planter, and 24.75 m for the sprayer. The features of machineries that were used in the experimental field operations are presented in e 2. Two types of GPS receivers (Fig. 2) were used for recording the positions of the vehicles involved. An AgGPS 162 Smart Antenna DGPS receiver (Trimble®, USA) with a Trimble® TMX-2050™ display (for storing the GPS data) was used for recording the trajectory of the bed former and the harvester, and three Aplicom A1 TRAX Data loggers (Aplicom®, Finland) were used for recording the trajectory of the stone separator, planter and sprayer. The recording frequency was set to 1 Hz in all experimental operations. Geo-referenced data were recorded continually including the non-working activities, *e.g.* turning, machine repair, operator break time. It has to be noted that only the activities of in-field machines were recorded, so the activities of transport units, *e.g.* the tractor for transporting seed potato from the farm to the field in planting, and for transporting harvested potato in harvesting were not monitored in the experiment. In addition, in planting and harvesting, the service units temporarily were placed at one position, and then moved to another position to facilitate the planter/harvester when it was necessary. The positions of the service units were recorded by using the Aplicom data logger for later GPS analysis. It has to be mentioned that field 9 was not harvested at all due to the influence of the weather.

Figure 2. The two types of GPS receivers used in the experiment.

Table 1. Experimental fields for case study.

Field shape	Field ID	Location	Area (ha)
	1	54º42´26.39´´N 11º19´30.20´´E	16.41
	2	54º42´19.15´´N 11º18´46.89´´E	22.74
	3	54º44´50.74´´N 11º12´55.79´´E	10.85
	4	54º50´18.00´´N 11º72´54.28´´E	19.73
	5	54º43´30.47´´N 11º16´47.47´´E	17.45
	6	54º52´13.07´´N 11º12´31.95´´E	7.50
	7	54º46´22.57´´N 11º25´01.07´´E	16.59
	8	54º44´28.22´´N 11º12´38.12´´E	22.04
	9	54º42´07.87´´N 11º18´46.22´´E	11.45
	10	54º57´30.71´´N 11º11´03.19´´E	13.55

Definition of time elements and machinery performance measures

In order to classify time elements, *e.g.* time spent on effective working, turning and pausing, etc., a range of time element definitions were made as described in Table 3. There exists the following relationship between the time elements:

$$T_{lost} = T_{tot} - T_{ef} = T_{turn} + T_{ld} + T_{trans} + T_{del}$$

Based on these time elements the field efficiency (FE, %) and the effective field capacity (EFC) for each operation in each field can be calculated, which is expressed as (Hunt, 2008):

$$FE = \frac{T_{ef}}{T_{ef} + T_{lost}} \times 100\%$$

Activities that contribute to delays, but take place outside the field, such as routinely maintenance, repair,

Table 2. Specifications of machineries involved in the potato production system.

Operation type	Operating width (m)	Load capacity
Bed former	4.5	–
Stone separator	2.25	–
Planter	2.25	3500 kg
Boom-type sprayer	24.75	3000 L
Harvester	2.25	7000 kg

and travel to and from the field, are not included in the estimation of FE.

The EFC of a machine can be calculated with two methods (Hanna, 2002). The first one is dividing the area completed by the hours of actual field time:

$$EFC = \frac{A}{T_{tot}}$$

where is the area of the field (ha). The second method is using the estimation equation:

$$EFC = S \cdot w \cdot FE / 100$$

where S is the working speed (km/h). The constant 1000 in the formula ensures that the unit of EFC becomes ha/h.

Analysis tool for GPS recordings

Based on the concept introduced by Bochtis & Sorensen (2009), these five operations can be categorized into three groups according to the flow of material into or out of the field: Material neutral operations (MNO) (bed formation and stone separation), material input operations (MIO) (planting and spraying), and material output operation (MOO) (harvesting). In order to analyse the data recorded during the execution of these operations, a dedicated tool was developed using the MATLAB ® suite (Mathworks, Natick, MA, USA). The input parameters of the tool include the coordinates of the field boundary and obstacle boundary (if any), the inner field boundary, *i.e.* the border between the headland and the main cropping area, and the coordinates of the machinery motion as well as the location of the service unit(s). The output consists of decomposed distance elements (*e.g.* effective working, turning, transporting, etc.) and the corresponding time elements.

The consecutively recorded data can be partitioned into line segments with sequential recorded data points by the field inner boundary. Those line segments that are located inside the main cropping area are considered as the on-the-tracks working motion trajectory while the line segments that are located in the headland area are considered non-working motion trajectory, such as turning, transporting, etc.

Due to the inherent inaccuracy of the speed measurements of GPS receivers the recorded position of a truly stopped machine may not be constant; consequently the machine is measured to have a slow movement. Therefore, to determine whether a machine is stopped or not, a threshold value v_{stop} is applied in each data point. The value of the v_{stop} parameter must be less than the usual operating speed and greater than the speed recorded due to the drift error. In this analysis v_{stop} = 0.02 m/s was used. The effective working time on each track corresponds to the total number of data points that have a speed greater than 0.02 m/s, so the total effective working time in the main cropping area is the summation of the effective working time on the tracks.

The non-working motion trajectory in the headland area may consist of four activities: turning, transporting, refilling and unloading. In MNO operations only the turning

Table 3. Time elements classification and definition.

Time elements	Symbol	Definition
Total operation time	T_{tot}	The total time spent in the field, *i.e.* the time span from the machine enters the field until it exits it after the completion of the operation.
Effective operating time	T_{ef}	The time the machine has worked productively in the field to complete the operation.
Turning time	T_{turn}	The total time of turning for changing the tracks at the headland area or crossing obstacle areas in the field.
Load/ unload time	T_{ld}	The time spent to load the material to the machine's hopper or tank (*e.g.* planter, sprayer) or to unload the material to the transportable storage units (harvesting).
In-field transport time	T_{trans}	The time spent on driving inside the field to loading or unloading areas.
Delay time	T_{del}	The total time during which the machine is not actually processing the field (such as operator rest stops, machine repair and maintenance time, and machine travel in the interior of a field) that occurs during the execution of the in-field operations.
Lost time	T_{lost}	The part of the total operating time, that is not effective.

activity occurs, while transporting occurs in both MIO and MOO operations. Finally, refilling and unloading occurs in MIO and MOO, respectively. To distinguish the turning, transporting, refilling/unloading activities in the headland area by the use of the recorded data points, circles were drawn with the radius of a given threshold value at the centres of the locations of the service units. If a machine stays inside the circle for a given threshold period of time, $T_{service}$, then the activity of the machine is categorized as being serviced and the transport time is the time on this motion trajectory minus the $T_{service}$. Otherwise, it can be considered as turning motion. The delay time in the headland area was calculated by isolating the sets of sequential points where the speed was lower than v_{stop}, 0.02 m/s. The value of $T_{service}$ was set to 10 min and 1 min for reloading in planting and unloading in harvesting, respectively. Fig. 3 presents a flow diagram of the analysis.

Field shape index

In this study, operations were carried out in different complexity levels corresponding to field shape. The FE for irregular field shapes is expected to be less than for rectangular fields due to excessive turning time. In order to investigate the effects of field geometry on the FE a shape index, MBR (Moser *et al.*, 2002), was used. MBR is defined as the ratio of the area of the field polygon and the area of the minimum bounding rectangle, and the index is used to describe the level of geometrical regularity of a field. The MBR is 1 for rectangles and approaches 0 when the shape becomes more irregular and odd. The calculated index values for the experimental fields are presented in Table 4. Furthermore, these index values were divided into two groups according the median value 0.78. These two groups were denoted as G1 (fields 1, 3, 5, 6 and 9 with MBR above the median) and G2 (fields 2, 4, 7, 8 and 10 with MBR below the median), respectively.

Results

Data recordings and analysis

In Fig. 4 the trajectory recordings of the bed former, stone separator, planter, sprayer and harvester in a selected field are presented. From the trajectories it is clear that the working width of the sprayer is much larger than the bed former, which is larger than the stone separator, the planter and the harvester. Fig. 4e gives

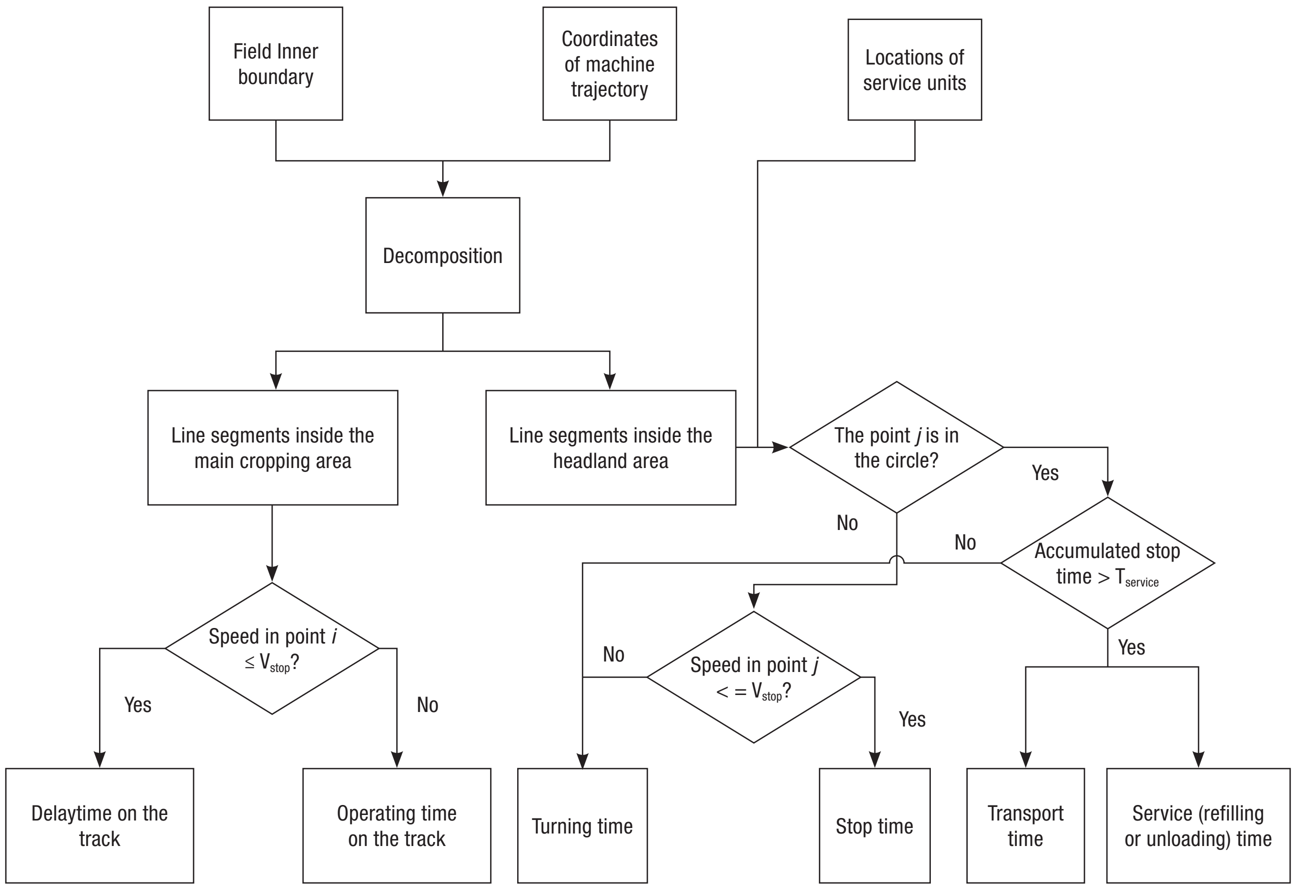


Figure 3. Flow diagram of the method of analysis of the recorded GPS data.

the false impression that some of the tracks have not been harvested. The reason for this, however, is that the harvesting happens on the right-hand side of the tractor, where the GPS receiver is mounted, as shown in Fig. 1e. Therefore, the field is always subdivided into blocks to reduce the non-working turning distance and time, and the harvester starts its harvesting from the middle bed of each block. This fieldwork pattern creates the gaps between blocks as shown in Fig. 4e.

The GPS data analysis also revealed that a few track skip turns (loop turns: Ω-turn or Π-turn) were made. Often these turns were executed at higher speed and with shorter turning distance compared to the fishtail turns. For instance, in bed forming, the measured average speeds for T, Ω (skip 1 track), and Π (skip 2 tracks) (as illustrated in Fig. 5) turns were 1.08 m/s, 1.15 m/s, and 1.35 m/s, respectively. The measured average turning distance for these three types of turns were 30.1 m, 31.2 m, and 23.3 m, respectively.

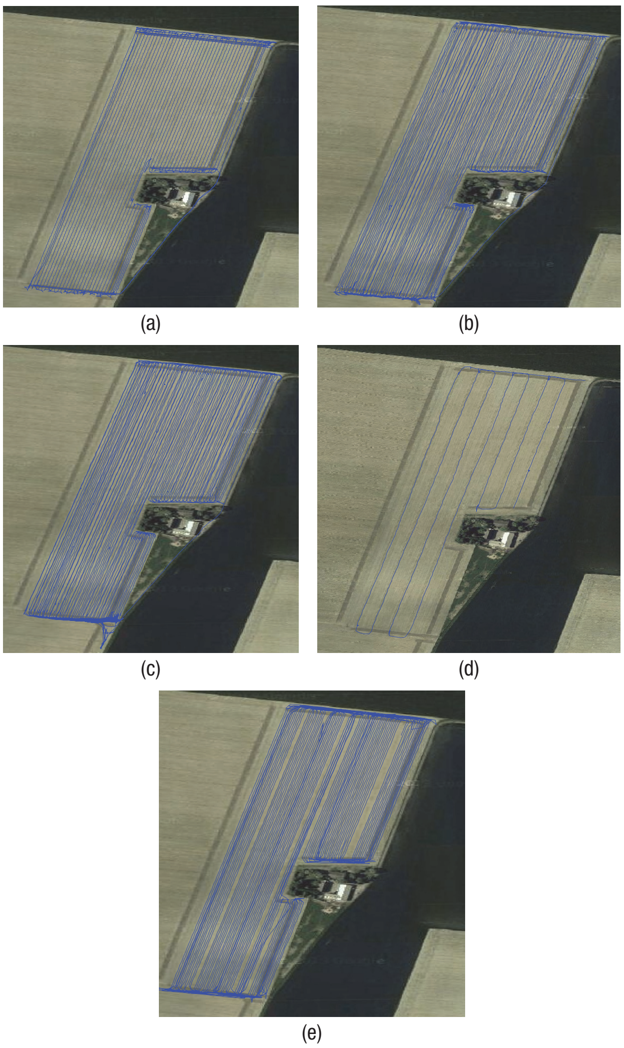


Figure 4. The GPS recordings for agricultural vehicles: (a) bed former, (b) stone separator, (c) planter, (d) sprayer, and (e) harvester in potato production in Field 3.

Table 4. Shape index values of MBR (minimal bounding rectangle) and index groups for the experimental fields.

Field ID	MBR	Index group
1	0.84	G1
2	0.74	G2
3	0.82	G1
4	0.63	G2
5	0.85	G1
6	0.92	G1
7	0.71	G2
8	0.72	G2
9	0.90	G1
10	0.56	G2

Classification of time elements

Figs. 6a to 6e show the distribution of the average operational time elements and FE for each machine in each of the ten fields for bed forming, stone separation, planting, spraying and harvesting, respectively. The measured FE for bed forming ranged from 58.4% to 78.7% with an average of 71.3%; for stone separation, the FE ranged from 65.7% to 73.4% with an average of 68.5%; for planting, the measured FE ranged from 31.9% to 48.3% with an average of 40.3%; for spraying the measured FE ranged from 53.2% to 76.8% with an average of 69.7%; finally, for harvesting the measured FE ranged from 59.0% to 72.8% with an average of 67.4%. Note, that even though spraying is a MIO the sprayer did not need to reload (Fig. 6d), since the tank capacity was sufficient even for largest field, and that field 9 was never harvested (Fig. 6e).

Field capacity distribution

Figs. 7a to 7e show the distribution of the EFC (calculated by the first method) for each machine in each of the ten fields for bed forming, stone separation, planting, spraying and harvesting. The measured field

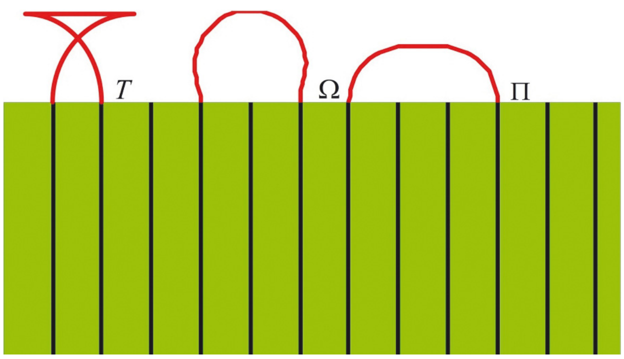


Figure 5. Three common types of turns T, Ω (skip 1 track), and Π (skip 2 tracks) used in bed forming.

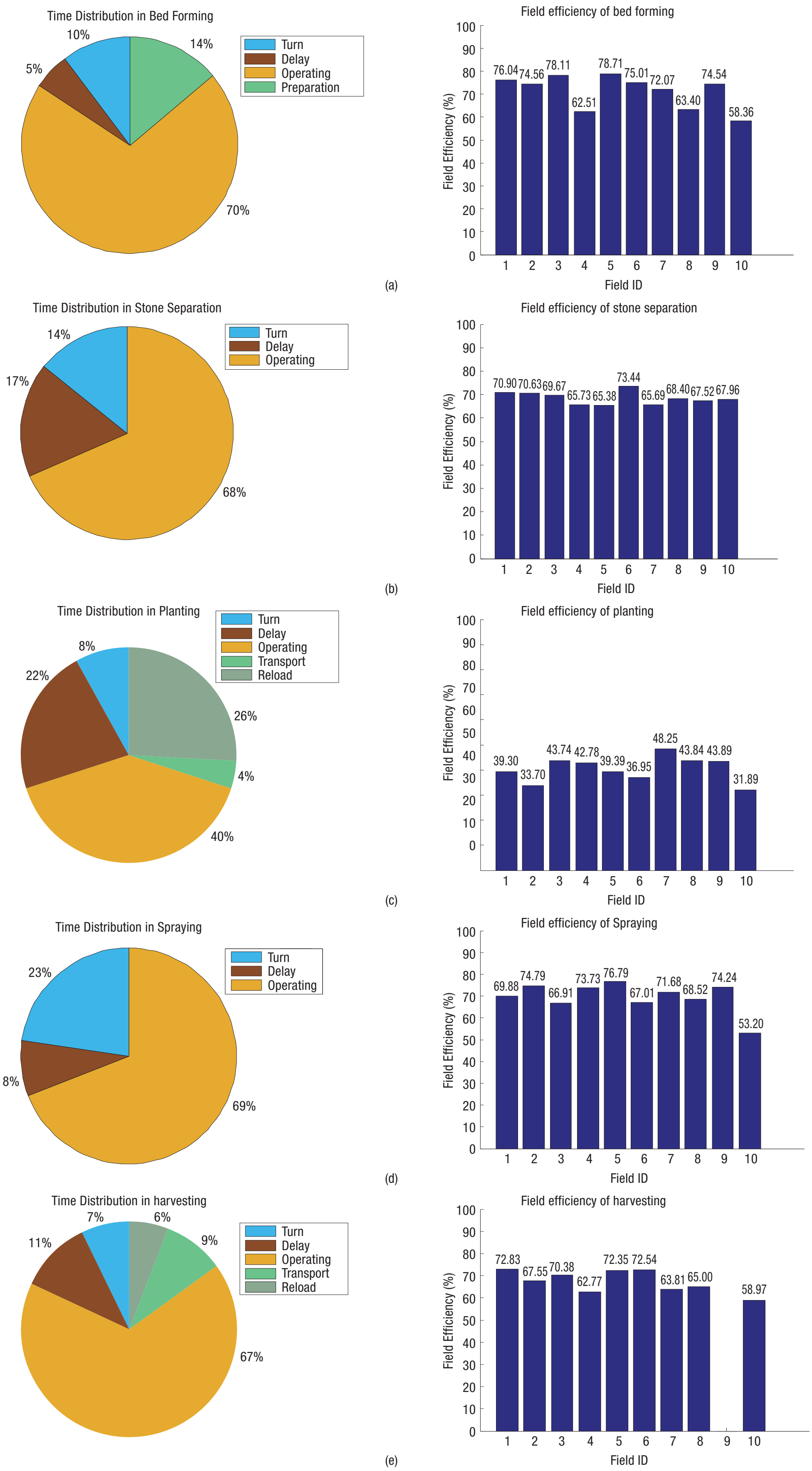


Figure 6. Time distribution in bed forming (a), stone separation (b), planting (c), spraying (d), and harvesting (e).

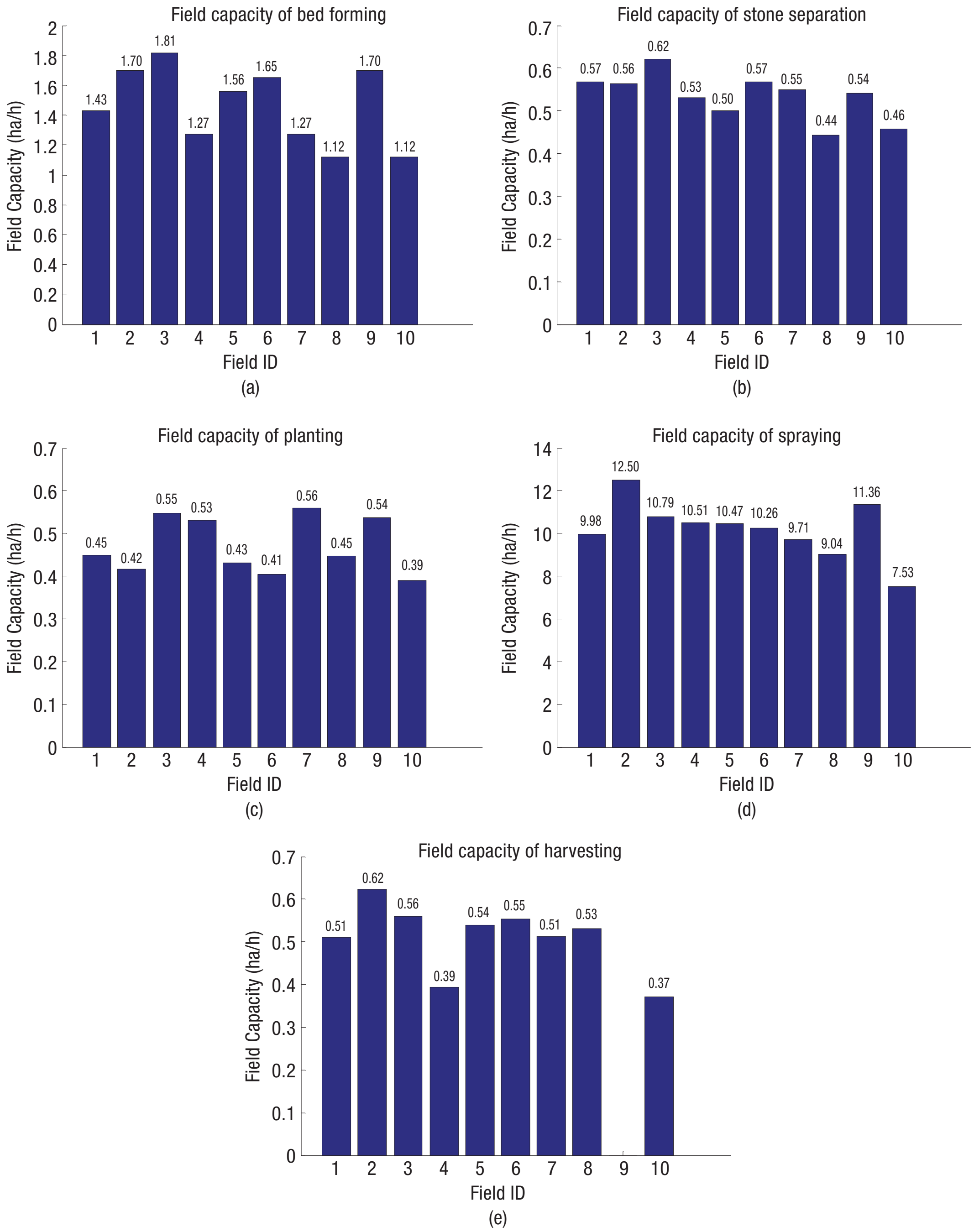


Figure 7. Field capacity distribution in bed forming (a), stone separation (b), planting (c), spraying (d) and harvesting (e).

capacity for bed forming ranged from 1.12 to 1.81 ha/h with an average of 1.46 ha/h; for stone separation, the measured field capacity was between 0.44 and 0.62 ha/h with an average of 0.53 ha/h. For planting, the measured field capacity ranged from 0.39 to 0.56 ha/h with an average of 0.47 ha/h. For spraying the measured field capacity ranged from 7.53 to 12.50 ha/h with an average of 10.21 ha/h. Finally, the measured field capacity for harvesting ranged from 0.37 to 0.62 ha/h with an average of 0.51 ha/h.

Comparison with ASABE norm data

The measured performance values of the machinery involved in the potato production were compared with the norms published by the Standard of the American Society of Agricultural and Biological Engineers (ASABE, 2011). The ASABE data give the FE and operating speed ranges with typical value for each machinery type. The selected values of FE from ASABE and calculated effective field capacity are presented in the

Table 5. However, there are no specific ASABE data provided for bed forming and stone separation.

Effect of field shape on field efficiency

Large variations were found in the measured FE and field capacity for the five main operations in the ten experimental fields. It was found that the group G1 with higher MBR index values had higher average FE. As shown in Table 6, the group of most regular fields, G1, had 10.4%, 1.8%, 0.5%, 2.6%, 8.4% higher FE than G2 in bed forming, stone separation, planting, spraying, harvesting, respectively. In terms of the field capacity, the group with higher index values also had higher average field capacity, except in the case of planting where both groups had the same average field capacity of 0.47 ha/h. The G1 fields had 0.33, 0.05, 0.7, and 0.05 ha/h higher field capacity than G2 in bed forming, stone separation, spraying, harvesting, respectively.

Discussion

The results of the analysis enable farmers to know exactly how efficient the machinery performed and which factors resulted in inefficiencies during the operations, subsequently to make better decisions on the operation planning in future cropping seasons. For example, the field shape may be one of the factors that affects the operational efficiency, and as illustrated in this study the fields with higher MBR values have higher FE than fields with lower MBR values. MBR is a measure of the level of regularity of a field where a rectangular field has value 1 and an extremely irregular field has a value approaching 0. Other researchers also used other shape indices to estimate the operational efficiency. Witney (1996) presented that a rectangular field with a 4:1 ratio between the lengths of its borders has highest value of efficiency and Oksanen (2013) developed a formula for estimating the operational efficiency using multiple shape indices based on multivariate regression. However, there are no general shape indices or formulas for estimation of operational efficiency of any type of fields.

In addition, the fieldwork pattern that defines the traversal sequence of the tracks also affects the time lost in the field due to non-productive travel (Hunt, 2008). A large portion of the non-working time takes place during the turning and/or transporting in the headland area. The turning time of a turn in the headland area depends on the distance and the turning speed.

Table 5. Comparison of our measured values and the ASABE (2011) norms of field efficiency (FE), field capacity (EFC) and operating speed.

	Measured			ASABE norm		
	FE (%) range (mean)	**EFC (ha/h) range (mean)**	**Operating speed (km/h) range (mean)**	**FE (%) range (typical)**	**EFC (ha/h) range (typical)**	**Operating speed (km/h) range (typical)**
Bed forming	58.4 - 78.7 (71.3)	1.12 - 1.81 (1.46)	4.9 - 5.2 (5.1)	–	–	–
Stone separation	65.7 - 73.4 (68.5)	0.44 - 0.62 (0.53)	3.4 - 3.8 (3.6)	–	–	–
Planting	31.9 - 48.3 (40.3)	0.39 - 0.56 (0.47)	5.0 - 5.5 (5.3)	55 - 80 (60)	1.11 - 2.16 (1.35)	9.0 - 12.0 (10.0)
Spraying	53.2 - 76.8 (69.7)	7.53 - 12.50 (10.21)	5.8 - 6.1 (5.9)	50 - 80 (65)	6.19 - 22.77 (16.89)	5.0 - 11.5 (10.5)
Harvesting	59.0 - 72.8 (67.4)	0.37 - 0.62 (0.51)	4.5 - 4.7 (4.6)	55 - 70 (60)	0.31 - 1.02 (0.54)	2.5 - 6.5 (4.0)

Table 6. Comparison of field efficiency (FE) and capacity (EFC) between field groups G1 and G2.

Operation type	FE (%)		EFC (ha/h)	
	G1	**G2**	**G1**	**G2**
Bed forming	76.50	66.10	1.63	1.30
Stone separation	69.40	67.60	0.56	0.51
Planting	40.60	40.10	0.47	0.47
Spraying	71.00	68.40	10.60	9.90
Harvesting	72.02	63.62	0.54	0.49

The selection of headland turning type potentially is determined by the fieldwork pattern and the width of the headland area under given working width and turning radius of the machine. The data analysis revealed that fishtail turns (T-turns) were commonly seen in bed forming and stone separation. The reason for this is the demand of manoeuvring space to approach an adjacent track of the T-turn. The disadvantage is that it is time demanding to make this turn, because the machine has to stop twice and shift gears to reverse the driving direction. For example, if the operator of the bed former uses the Π turns to cover the whole field, the FE can be improved from 75.0% to 77.3% in field 6. Hence, adoption of appropriate fieldwork pattern for field coverage can improve the performance of the machinery. There are additional potential advantages of using an optimal standard fieldwork pattern. In general, the optimal fieldwork pattern mainly consists of easy steering turns (*e.g.* Ω-turns and Π-turns), which not only reduce the operational cost but also reduce the fatigue of the operator (Holpp *et al.*, 2013) making it possible for the operator to work efficiently for longer periods and at a consistently high level of work quality. Other existing routing methods, such as the B-pattern, introduced by Bochtis & Vougioukas (2008), which computes the optimal track sequence towards minimization of the total non-working turning distance, requires developing a dedicated tool for each agricultural vehicle to implement this type of pattern in each operation. Nevertheless, these standard fieldwork patterns can be directly implemented in the currently available navigation-aiding systems (*e.g.* iTEC Pro®, John Deere) and it is not even necessary to mount navigation-aiding systems on tractors for each operation in the case of bed crop production, because operators of the subsequent operations after bed forming can easily distinguish the next track to be followed, since the beds are already clearly formed. In this way, the farmers do not need to purchase extra and multiple navigation-aiding systems. In addition, the capacity of the machinery and the locations of the service unit (SU) also have effect on the FE. Bochtis *et al.* (2010) and Zhou *et al.* (2015) have evaluated different user configurations in terms of machinery capacity and locations of the SU on the effect of the FE by using simulation models. The research results show that appropriate selections of machinery capacity and SU's locations can substantially increase the FE from 35.5% to 69.1%.

By comparing the average measured values of FE and capacity with the norm values issued by ASABE (Table 5), it can be found that the measured values were lower than the norms. These deviations can partially be explained by differences of the suggested and measured working speeds. The ranges of FE of spraying and harvesting were within in the ranges of ASABE norm data, while in the planting the measured highest FE was even lower than the lowest FE of ASABE provided. Therefore, it is obvious that the ASABE norms cannot be used directly for sufficiently predicting performance of machinery, at least in the potato production system of this study. In addition, the measured field efficiencies and capacities in bed forming and stone separation could be used as supplementary data for ASABE norms, since specific data for these two operations are not provided by ASABE.

The performance analysis of machineries involved in the potato production in one growing season is very important for farm manager to make a strategic operation plan in terms of machinery and labour demands. Moreover, the presented analysis results provide the basis for development of a dedicated simulation model encompassing all field operations in potato production. This dedicated model can help farmers to make global planning by taking into account features of machinery (*e.g.* tank size, working width) and fields (*e.g.* field boundary, working directions) in all involved operations as well as quantitatively estimate and predict the operational time and cost. This is the subject of future research based on the present work.

In summary, in this study, GPS data of the machine motions in the five main operations in potato production (bed forming, stone separation, planting, spraying and harvesting) were gathered and analysed from ten fields in one growing season. The performance measures field efficiency and field capacity was calculated for each operation in each field based on the extracted task time elements from the recorded data. These calculated field efficiencies and capacities differ from the corresponding norms given by ASABE. This deviation indicates that ASABE norms cannot be used directly for predicting performance of the machines used in this study. Furthermore, the development of a dedicated model including all five operations for potato production based on the statistical analysis from monitored operations is a necessity, which can help farm managers make strategic and operational plans for the entire growing season in terms of machinery and labour demands and costs under given field conditions.

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