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Corn seeding process fault cause analysis based on a theoretical and experimental approach

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ABSTRACT

Contemporary trends have set the need for high precision systems in agricultural operations, but it is the seeding technology in the first place that must satisfy the toughest demands to achieve the highest possible profit. The improvement of seeding precision is impossible without knowledge of the working principles of all parts of a singulation mechanism and all factors which influence the seeding errors. The evolution of a seeder depended crucially on the improvement of the testing methodology and techniques. This paper presents a photo-electronic device which monitors the seed flow at free fall after leaving the seeding mechanism. An air blowing seeding mechanism was used to simulate the seeding. Its performances were tested with seven varieties of corn seed, two seeding plates, two different air flow rates, and four different speeds of revolution of the seeding plate. A full factorial design was used to determine the significance of influence of four input factors and interactions of two of them. Data validation was done by comparing the values calculated according to visual analysis of high-speed camera recordings and photo-electronic system data where a strong relationship was achieved ($R^2 > 0.99$). It was determined that the speed of revolution of the seeding plate had the greatest influence on the varying distance between the consecutive seeds, while the seed variety exerted the least influence. The pressure of air flow and the variety of the seeds had the most significant influence on the variation of quality of feed index, although, the type and speed of revolution of the seeding plate were also statistically significant parameters. The occurrence of miss and multiple seed were caused by air flow pressure, variety of the seeds, type of the seeding plate, i.e., speed of revolution of the seeding plate. The applied optimization method can be a useful tool for finding the best possible combination of input parameters observed in the test in order to fulfill the criteria which vary depending on the user's needs.

1. Introduction

In modern crop farming production systems, soil treatment is changing in the direction of decreasing the intensity of soil tillage (Kostić et al., 2016, Biddoccu et al., 2016). Hence, field conditions have become more difficult (soil is less homogenous, more compacted with greater presence of plant residue), and high accuracy of seed dosage and field germination is far more complex to achieve (Farooq and Siddique, 2015; Kassam et al., 2014). A large number of agricultural experts agree that seeding quality plays an important role in field crop production (Cay et al., 2018; Karayel and Ozmerzi, 2002). If plants are given equal access to all field resources, favorable preconditions can be created to maximize the genetic potential of the variety-hybrid. Equal spatial distribution of plants provides optimal conditions for each plant, thus reducing the competition between them (Heege, 1993; Griepentrog, 1998; Karayel and Ozmerzi, 2002). The importance of plant arrangement in the field with respect to the quality and yield size depends on the plant species. In general, increased inter-row and inner-row seed distance implies greater importance of uniform distribution of plants, and vice versa. Jaggard (1990) emphasizes the importance of precision seeding in the production of sugar beet because uneven distance of the seeds affects the unequal growth and formation of the roots, thus reducing the effectiveness of a harvester. Seeding quality affects effectiveness of weed control during the vegetation period, as the possibility of weed spreading increases with more empty spaces which is the result of a seeding error. Lan et al. (1999) state that seeding affects directly the final yield and indirectly the financial effects of production. Mechanical herbicide-free control of sugar beet by

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longitudinal and lateral tractor drive requires the formation of a rectangular plant arrangement (Schölderle et al., 2008). Robinson et al. (1982) found that sunflower yield in Minnesota decreased up to 30% due to an uneven distribution of seeds.

Regarding the seed dosage process and all the relevant factors, Kostić et al. (2011) recognize "external" and "internal" factors which affect the quality of seeding. The external factors are variables that are not related to the design of the seeding mechanism but still influence the seeding errors. Those are the seeder ground speed, physical properties of the seed, soil roughness, terrain inclination, etc. Most of these variables are erratic and the degree of their influence is impossible to predict. Internal factors relate to technical characteristics of the seeding apparatus, such as kinematics of the seeding device, efficiency of seed ejector and excess seed remover, transmission drive system, the type of seed feeding device, the mode of transporting the seeds to the furrows, seeding mechanism clearance to the ground, etc. Fornstrom and Miller (1989) state that the operating speed and the way the seed is ejected to open furrows are essential elements of the precision seeding.

The quality of seeder operations is evaluated by standard statistical indicators that are calculated based on the data from which extreme values were excluded (less than 0.5 seed spacing and bigger than 1.5 seed spacing) in accordance with the general rules defined by the standard ISO 7256/1. The most widely used parameter is CV (*coefficient of variation*) as average relative deviation of the measured distance from the mean value. Kachman and Smith (1995) claim that precision seeding involves variability less than 30%, while Griepentrog (1998) and Celik et al. (2007) claim that this variability is below 20%. Irla and Heusser (1991) state that an acceptable quality of feed index (the percentage of spacings that are greater than half but not greater than 1.5 times than the set seeding distance in mm) for precision seeding should be over 90%. This phenomenon depends more on the average seed distance than on the absolute spacing error and could be inadequate for the estimation of seeding quality, which was also observed and explained in detail by Müller et al. (2006). Smith et al. (1991) and Kachman and Smith (1995) define a Coefficient of Precision-CP3 (percentage of the spacings that are within ± 15 mm of the set seeding distance) parameter to estimate the seeding quality. This parameter is combined with other statistical indicators (arithmetic mean and standard deviation).

The precision of seeders can be tested in real in-field conditions, where all objective factors are involved, or in controlled conditions in the laboratory, where seeding is simulated using the appropriate devices and omitting the "external" factors (McLean, 1974; Hollewell, 1982; Thomson, 1986; Brooks and Church, 1987; Hofman, 1988; Kachman and Smith, 1995; Bracy et al., 1998; Özmerzi and Karayel, 1999; Özmerzi et al., 2002). In-field quality control is a method typically used by agricultural practitioners but it has some disadvantages. Determination of the seeding quality in the field can be carried out after the plant seeding or germination. If it is carried out after the germination, then there is a probability of occurrence of certain measurement errors due to the factors which are not related to the seeder operation. These factors are germination and sprouting strength of the seed, as well as the inhomogeneity of moisture distribution in the zone of the seed layer, the influence of pests, quality of soil preparation, etc. If the measurement is performed immediately after the seeding, it is necessary to dig out a few seeds from particular field zones with a certain number of repetitions. The required number of examination sections depends on the number of row units of the seeder. This technique reduces the relevance of the measured data due to the disturbance of the actual seed position during digging. Additionally, it is impossible to obtain a sufficient amount of data since the technique is time consuming. Contrary to the in-field method, a laboratory technique is more often used in simulating the seeding conditions, since it allows a detailed analysis of the seeding mechanism efficiency irrespectively of the influence of other factors (rolling of the seed in a furrow, influence of the fall height, vibrations) which present real conditions. The relative movement of the seeder on the surface is simulated while the revolution of the seeding plate is controlled by electronic regulation of the drive motor as well as the power of the air flow. Simulation of seeding along the adhesive endless tape is the first laboratory technique characterized by a small number of valid samples in one measurement session and other defects that are explained in detail by Kocher et al. (1998). Laboratory evaluation of the seeding mechanism quality uses advanced systems such as optical sensors (Kocher et al., 1998; Lan et al., 1999). The system consists of a control unit connected to a PC and a software interface to read the records from a sensor that measures the pass time intervals of two consecutive seeds and the location of the seed passing through the sensor. Another innovative approach was presented by Karimi et al. (2009) which involves conversion of acoustic effects of seeds hitting the membrane into an electric signal with spectral characteristics. Post-processing analysis uses these characteristics to obtain the seeding distances from simulated seeding. Laboratory evaluation of the seeding mechanism was done by Navid et al. (2011) using the method of image processing from a camera. A comparative analysis of the measured distances with image processing techniques and adhesive tape measurement gave calibration characteristics that indicated high reliability of image processing. Authors point out that in relation to the optoelectronic system, image processing is more favorable because it is not sensitive to the size of the seed, or to the detection of multiple seeds. Karayel et al. (2006) applied high-speed image detection in laboratory measurements of seed spacing. The system was tested under conditions of high-frequency flow of small and large seeds in order to confirm the system's operation in the most complex circumstances. The recording was performed at 700 Hz sampling rates using video processing software. It was concluded that no seed was missed and that a high coefficient of data accuracy was established by comparing the data obtained by a standard measurement method with adhesive tape. A disadvantage of the method is a complicated procedure of extraction and processing images in the software.

The primary goal of this research is to validate the possibilities of photosensor evaluation method using data and image analysis in simulated conditions. Also we would like to reveal the strength of influence of observed variables on the seeding distribution accuracy.

2. Material and method

2.1. Theoretical analysis of real influences on the seed free fall trajectory

This analysis takes into account all variables that affect the motion of the seed immediately before and after leaving the seeding mechanism, except the influence of the air resistance and the aerodynamics of the seed during its fall. When leaving the seeding device, seed path is most often approximated by a projectile motion with a horizontal and vertical component of the velocity, which further defines the range of the starting point of ejection. Kocher et al. (1998) explained the irrelevance of determination of the seeded seeds distances based on the measured seed drop intervals only because of the variable path of the seed fall. Hypothetically, the falling time interval of two consecutive seeds can differ, although seed ejection time intervals are identical, which introduces an additional variable. In that sense, the resulting component of seed fall velocity had a dominant influence on the location of the seed drop. The analysis was carried out in order to define the components that influence seed kinematics.

Depending on the design of the seeding mechanism (diameter of seeding plate and number of holes) and the desired seeding rate, the ground speed of the seeder is usually different from the peripheral speed of the seeding plate, so the resulting horizontal component of the seed velocity most often has direction towards the movement of the seeder. The intensity of the seed rolling into the open furrow is proportional to the ratio between the horizontal component of seed velocity and ground velocity. A higher operating speed causes the speed difference between the ejected seed and seeder to increase as well. Thus

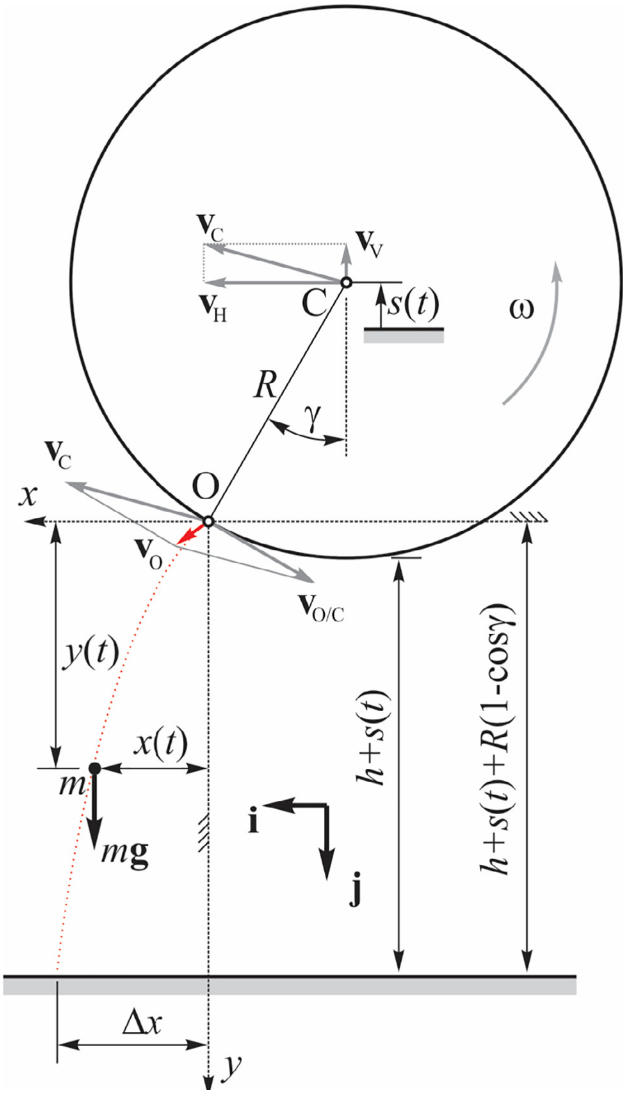

Fig. 1. Kinematic of ejected seed.

the probability of moving the seed in the open furrow increases, too (Panning et al., 2000). Prior to defining the seed trajectory, there are variables that must be taken into account and that are not considered in the laboratory testing. These variables are the current vertical position of the seeding mechanism relative to the ground, the value of peripheral speed of seeding plate, initial seed position before the ejection from the seeding mechanism (Fig. 1), and vibrations. In real seeding conditions, the seed fall height varies at certain intervals depending on the surface roughness which affects seed falling time. Also in real field conditions the seeders with a mechanical drive of the seeding plate have a nonstationary ratio of the ground speed and the angular velocity of the seeding plate due to the appearance of “asynchronous transmission” and “pulse rotation” which affects the change in the initial seed velocity. Asynchronous transmission is a time inconsistent kinematic ratio of the transmission speed of the seeder and the peripheral speed of the seeding plate due to the variable drive wheel slippage. The pulsating rotation on the other hand represents the harmonic pulsating oscillations of the seeding plate which occurs as a consequence of the unequal adhesion between the elements of drive transmission (transmission gears, transmission chains) and disturbances in fitting quality after a certain period of exploitation. The intensity of vibrations and its influence on the seeding mechanism efficiency were studied by Manquan et al. (2012). Machine vibrations consist of periodic and erratic components with different frequency and oscillation amplitudes of the device, which may be of interest for future studies. The location of seed ejection from the seeding mechanism affects the ratio of vertical and horizontal components of the seed fall velocity. This in turn changes the sensitivity of the seeding mechanism and operational precision. The seed trajectory has been simplified by other authors in past approaches. They roughly accept that the seed motion trajectory corresponds to projectile motion form, omitting overall factors that affect initial conditions of seed motion. The motion of the ejected seed was considered the factor that affects the initial conditions of seed motion after ejection from the seeding plate.

Let $\vec{\mathbf{v}}_\mathrm{O}$ be the initial velocity vector with projections on the coordinate axes $v_{\mathrm{O}x}\,\vec{\mathbf{i}}$ and $v_{\mathrm{O}y}\,\vec{\mathbf{j}}$, so

$$\vec{\mathbf{v}}_\mathrm{O} = v_{\mathrm{O}x}\,\vec{\mathbf{i}} + v_{\mathrm{O}y}\,\vec{\mathbf{j}}\,. \tag{1}$$

If there is vertical movement of point C (center of the seeding plate), then the following stands for initial velocity vector (Fig. 1)

$$\begin{aligned}\vec{\mathbf{v}}_\mathrm{O} &= \vec{\mathbf{v}}_\mathrm{C} + \vec{\mathbf{v}}_\mathrm{O/C} = \vec{\mathbf{v}}_\mathrm{H} + \vec{\mathbf{v}}_\mathrm{V} + \vec{\mathbf{v}}_\mathrm{O/C} = \vec{\mathbf{v}}_\mathrm{H} - \dot{s}\,\vec{\mathbf{j}} + \vec{\mathbf{v}}_\mathrm{O/C}\\ &= v_\mathrm{H}\,\vec{\mathbf{i}} - \dot{s}\,\vec{\mathbf{j}} + (-R\omega\cos\gamma\,\vec{\mathbf{i}} + R\omega\sin\gamma\,\vec{\mathbf{j}}\,) = (v_\mathrm{H} - R\omega\cos\gamma)\,\vec{\mathbf{i}}\\ &\quad + (R\omega\sin\gamma - \dot{s})\,\vec{\mathbf{j}}\end{aligned}$$

and, using (1), we have

$$v_{\mathrm{O}x} = v_\mathrm{H} - R\bar{\omega}\cos\gamma,\ v_{\mathrm{O}y} = R\bar{\omega}\sin\gamma - \dot{s}\,(t), \tag{2}$$

where $\bar{t}$ – seed release time (projectile motion begins), $\bar{\omega}$ – angular speed of seeding plate at time $\bar{t}$, $\dot{s}\,(\bar{t})$ – velocity of the center of seeding plate at time $\bar{t}$ in vertical direction, R – radius of the seeding plate, γ – angle that defines the position of seed ejection and v_H – seeder velocity.

The initial conditions for free fall in the fixed $x\mathrm{O}y$ coordinate system are

$$x(\bar{t}) = 0, \tag{3}$$

$$y(\bar{t}) = 0, \tag{4}$$

$$\dot{x}(\bar{t}) = v_{Ox} = v_H - R\bar{\omega}\cos\gamma, \tag{5}$$

$$\dot{y}(\bar{t}) = v_{Oy} = R\bar{\omega}\sin\gamma - \dot{s}(\bar{t}). \tag{6}$$

According to Newton's second law of motion, the seed free fall is $m\,\mathbf{a} = m\,\mathbf{g}$, and its projections on the coordinate axes (differential equations of motion) are

$$\ddot{x} = 0, \tag{7}$$

$$\ddot{y} = g. \tag{8}$$

Integrating (7) twice, using initial conditions (3) and (5) we get

$$x(t) = v_{Ox}(t - \bar{t}), \tag{9}$$

while integrating (8) twice, with (4) and (6) we get

$$y(t) = \frac{1}{2}g(t - \bar{t})^2 + v_{Oy}(t - \bar{t}). \tag{10}$$

2.1.1. Determining the range

By eliminating time t from the motion equations (9) and (10), the trajectory equation becomes

$$y(x) = \frac{1}{2}g\left(\frac{x}{v_{Ox}}\right)^2 + v_{Oy}\frac{x}{v_{Ox}}. \tag{11}$$

Coordinate x becomes range Δx for $y = h + s(\bar{t}) + R(1 - \cos\gamma)$. Then, (11) implies

$$\Delta x = \frac{v_{Ox}}{g}\left(-v_{Oy} + \sqrt{(v_{Oy})^2 + 2gh + 2gs(\bar{t}) + 2gR(1 - \cos\gamma)}\right), \tag{12a}$$

i.e.

$$\Delta x = \frac{v_H - R\bar{\omega}\cos\gamma}{g}\left(-R\bar{\omega}\sin\gamma + \dot{s}(\bar{t}) + \sqrt{(R\bar{\omega}\sin\gamma - \dot{s}(\bar{t}))^2 + 2gh + 2gs(\bar{t}) + 2gR(1-\cos\gamma)}\right), \tag{12b}$$

where $s(\bar{t})$ – movement of the center of the seeding plate in vertical direction at time $\bar{t}$.

2.1.2. Determining the seed free fall time

At final time $t = t_k$, when seed ends its motion, its x coordinate, according to (9), (12a) and (12b), is $x(t_k) = \Delta x = v_{Ox}(t_k - \bar{t})$, so seed free fall time is

$$\Delta t = t_k - \bar{t} = \frac{1}{g}\left[-R\bar{\omega}\sin\gamma + \dot{s}(\bar{t}) + \sqrt{(R\bar{\omega}\sin\gamma - \dot{s}(\bar{t}))^2 + 2gh + 2gs(\bar{t}) + 2gR(1-\cos\gamma)}\right]. \tag{13}$$

2.2. Design of laboratory experiment

An air-blowing precision seeding mechanism Massey Fergusson 555 was used in this research. The diameter of the seeding plate was 320 mm with 30 cells in a vertical plane. The analysis of the seeding distribution accuracy was based on the data from the measurement of seed distance in simulated conditions, using the prepared laboratory configuration. Seeding plate revolutions were regulated by changing the speed of the drive motor with the frequency regulator in a range from 0 to 25 rpm giving the maximum seeding frequency of 12 seeds per second. The fan was also driven by an independent electric motor, while air flow was adjusted by changing the revolution speed of the drive motor. Pressure control was performed visually with an analog pressure gauge. The entire system was installed on a pedestal support. The testing was performed with a seeding plate SP1 (No. 852434) with “larger cells” and a seeding plate SP2 (No. 852435) with “smaller cells” (Fig. 2), at a pressure of 254 Pa and 635 Pa with a four rotation speed of plate (6, 12, 19 and 26 rpm). The rotation speed of the seeding plate was calculated according to the desired distance between the seeds and the simulated seeder speed (v_{S1} = 0.6 m/s; v_{S2} = 1.2 m/s; v_{S3} = 1.9 m/s; v_{S4} = 2.5 m/s). The seeding distance was 0.2 m which did not change during the test. The testing was performed with seven corn seed varieties. Corn is one of the most produced cereal crop in many regions of the world with 180 million hectares which takes almost 25% of the total world's cereal area (Roser and Ritchie, 2018). In Serbia likewise almost 50% of total arable fields are used for corn production. Hence, the seeding precision of corn has an important role in the achievement of high yields. The average dimensions and parameters of the seed shape were obtained based on the analysis of 100 seed samples (Table 1) and compared with the ANOVA test at p = 0.05 level. Seed dimensions were measured with a vernier caliper of 0.01 mm accuracy. The parameter sphericity was calculated according to the model used in Davies and Zibokere (2011). The arithmetic mean diameter, geometric mean diameter and surface area were calculated the same way Altuntas and Yildiz (2007) did:

$$Sp = \frac{(LWT)^{\frac{1}{3}}}{L} \times 100 \tag{14}$$

$$Da = \frac{(L + W + T)}{3} \tag{15}$$

$$Dg = (L\cdot W\cdot T)^{\frac{1}{3}} \tag{16}$$

$$S = \pi\cdot Dg^2 \tag{17}$$

where Sp is the sphericity, Da is the arithmetic mean diameter, Dg is the geometric mean diameter, S is the surface area, L is the length, W is the width, T is the thickness.

Based on the ANOVA test results (Table 1) it is evident that the varieties differ significantly in at least one dimension. The shape indicators show mild distinction between the groups of data where similarity is observed between the F-2 and F-4 varieties, or F-5 and F-6.

A laboratory experiment was conducted as a random block design with a total of 112 trials to combine all independent parameters (2 seeding plates × 2 air pressures × 4 revolutions × 7 varieties). Each measurement session generated 299 values of the distance between successive seeds, which was a total of around 33,000 samples.

2.2.1. Laboratory evaluation of seeding precision

The distance between the seeded seeds was measured with an electronic device that was previously designed for that purpose. In the

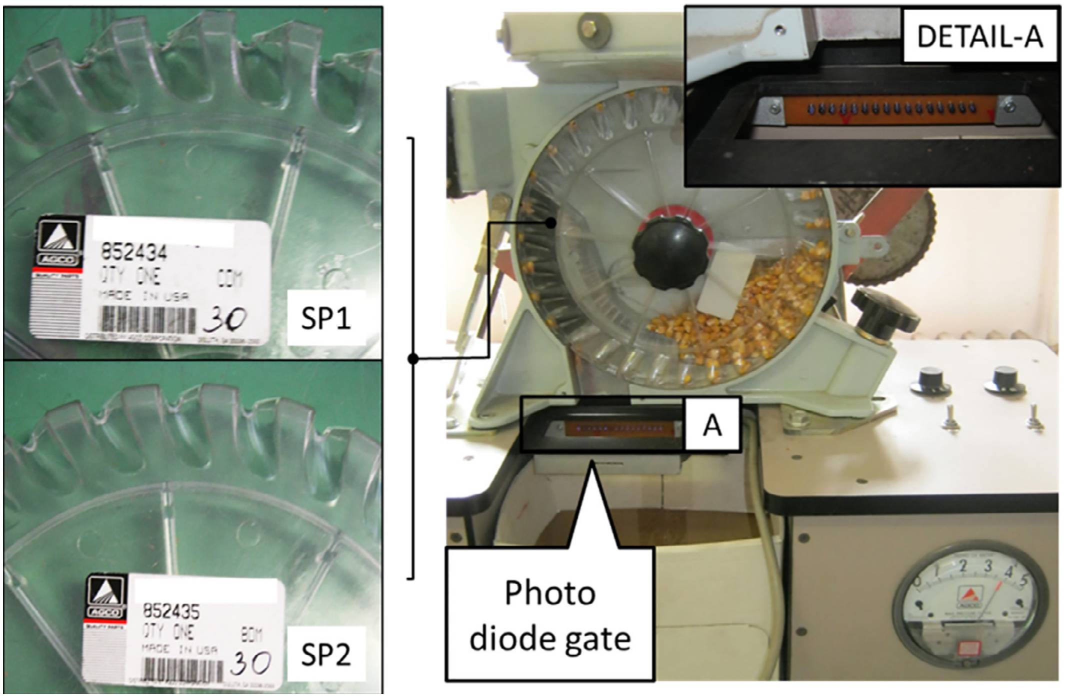

Fig. 2. Seed metering device with installed photo-sensor (diode panel) with seeding plates SP1 and SP2.

Table 1
ANOVA analysis of dimension parameters of corn seed varieties.

Seed fraction	Mass of 1000 seeds, g	Length, mm	Width, mm	Thickness, mm	Sphericity, % (Sp)	Arithmetic mean, mm (Da)	Geometric mean, mm (Dg)	Surface area, mm^2 (S)
F-1	266	$10.34^{b} \pm 0.90$	$8.09^{b} \pm 0.72$	$5.14^{b} \pm 1.06$	$0.73^{b} \pm 0.09$	$7.85^{b} \pm 0.41$	$7.49^{b} \pm 0.50$	$177.03^{b} \pm 23.88$
F-2	228	$10.33^{b} \pm 0.78$	$7.60^{a} \pm 0.47$	$4.83^{ab} \pm 0.86$	$0.70^{ab} \pm 0.07$	$7.58^{a} \pm 0.36$	$7.20^{a} \pm 0.42$	$163.43^{a} \pm 19.03$
F-3	287	$10.7^{bc} \pm 0.63$	$8.72^{c} \pm 0.52$	$4.98^{b} \pm 0.86$	$0.72^{b} \pm 0.06$	$8.13^{c} \pm 0.36$	$7.72^{b} \pm 0.46$	$187.54^{b} \pm 22.81$
F-4	233	$10.59^{bc} \pm 0.75$	$7.41^{a} \pm 0.46$	$4.53^{a} \pm 0.42$	$0.67^{a} \pm 0.04$	$7.51^{a} \pm 0.28$	$7.07^{a} \pm 0.26$	$157.12^{a} \pm 57.12$
F-5	256	$9.28^{a} \pm 0.84$	$7.57^{a} \pm 0.76$	$6.23^{c} \pm 0.64$	$0.82^{c} \pm 0.07$	$7.69^{ab} \pm 0.47$	$7.57^{b} \pm 0.47$	$180.64^{b} \pm 22.18$
F-6	284	$10.84^{c} \pm 0.49$	$8.56^{c} \pm 0.47$	$4.73^{ab} \pm 0.59$	$0.70^{ab} \pm .04$	$8.04^{c} \pm 0.30$	$7.58^{b} \pm 0.37$	$180.98^{b} \pm 17.19$
F-7	321	$9.43^{a} \pm 0.67$	$8.87^{c} \pm 0.76$	$6.76^{d} \pm 0.74$	$0.88^{d} \pm 0.05$	$8.35^{d} \pm 0.43$	$8.24^{c} \pm 0.44$	$214.01^{c} \pm 22.83$

^{abcd}Letters represent different classes obtained by ANOVA with $p = 0.05$ level of significance.

simulated seeding conditions, the device allows immediate evaluation of seeding quality (Coeff. of variation, Standard deviation, Number of misses, Number of doubles, Mean seed spacing) for different seeding mechanism designs based on the measured distance between successive seeds.

2.2.1.1. *Description of electronic device for seeding simulation.*

(1) Optical sensor – consisting of 16 emitting diodes (SFH309) and 16 phototransistors (SFH409) which works in IR wavelength range ($\lambda_{max} \approx 950$ nm) with a diameter of 3 mm in two parallel rows making photogates (Fig. 2). Each emitting diode is located exactly opposite the corresponding phototransistor (Kocher et al., 1998). The distance of the optoelements in the row is 5 mm, while the distance between the phototransistor row from the row of the photodiode is 40 mm. The photoelements are placed on a plastic plate with an opening for the seed to pass. When the seed passes through the sensor gate a shadow is created at the point of passage which causes a reduced current flow through a phototransistor. This is further processed in the control unit and the distance is calculated in relation to the previously recorded time and location of the seed pass;

(2) Shaft encoder with 120 pulses per revolution (AINS 41, Meyer Industrie-Electronic GmbH) – detects shaft rotation of the seeding plate in real time. The data on the rotational speed of the seeding plate is used to calculate the ratio of the simulated seeding speed and the peripheral speed of the seeding plate. Based on the number of seeding plate cells, the system recalculates the seed spacing, i.e. calculates the deviations;

(3) PC with software – collects and processes data and visualizes the results. The obtained distance is calculated on the basis of the time interval between two seeds ejected consecutively. There is a simulated ground speed and the difference in the horizontal distance between the passage point of the two consecutive seeds detected by the photosensor with a resolution of 5 mm. If there are two phototransistors overshadowed by a larger seed, the system automatically calculates the average coordinate. The software generates a distribution diagram of the achieved seed distances and basic statistical parameters (average distance, number of misses and multiple, standard deviation and coefficient of variation). The PC software was created with Delphi (Embarcadero RAD Studio XE6).

(4) The main electronic unit – converts the analog to a digital signal transmitted to the PC via RS232 communication port and software interface (Fig. 3). The reading of the optical sensor is performed every 30.5 µs. A PIC16F877A microcontroller was used in the system which was programmed in MicroBasic scripting language.

2.2.1.2. Validation of measured distances. The validation of measured distances was performed with one corn variety and a SP1 seeding plate on a sample of 50 seeds (49 valid seed spacings obtained in an optimal operating mode) for four peripheral seeding plate speeds (6, 12, 19 and 26 rpm) in two repetitions. The adjusted seed spacing was 0.2 m. Recordings (time and relative displacement of the seed location) were compared with the calculated values of the actual distances obtained from the high-speed recordings processed by Olympus SH-60 camera. Video recordings with 324 × 432 resolution were obtained at a speed of 240 frames per second where the time interval between the two frames was 0.004 s. The time intervals between the two seeds were measured with a high-precision stopwatch with 0.001 s resolution which is an integral part of the photo electronic device. Time intervals between passes of consecutive seeds are available in form of a list after each processed test. Maximal possible error was ± 0.005 m for the simulated spacing between the seeds with the rotational speed of the seeding plate being maximum (25 rpm). The probability of occurrence of this type of error is stochastic and it is impossible to predict the frequency of its formation due to a large number of factors that affect the trajectory and the time of the seed fall. In order to monitor the fall path of the seed and locate the seed passage through the sensor gate, a surface with black and white fields (5 × 5 mm), like a chess board, was placed behind the sensor. Analysis of recorded video was performed by visual inspection of each individual frame and by writing down the time and relative coordinates of the seed position at the moment of entry into the sensor zone (Fig. 4). Parameters were later manually entered in the Excel table for further processing. The occurrence of a single miss and a double miss in the record was caused by closing every 10th cell on the disk, and respectively, every ninth and tenth cell on the seeding plate. This approach provided synchronization of the data series, obtained with an electronic device and image-based distance values. A similar procedure was applied by Kocher et al. (1998) and Lan et al. (1999). In general, whether the video recording is processed by a software or visually, like in this research, time engagement is required, as noted by Karayel et al. (2006) who used image processing software. Authors who developed similar devices used standard laboratory equipment with an adhesive band for data validation. In that case, the sensor was placed above the adhesive band at a defined distance which implies a necessary correction of the horizontal coordinate of the sensor data due to the parabolic path of the seed from the sensor to the tape.

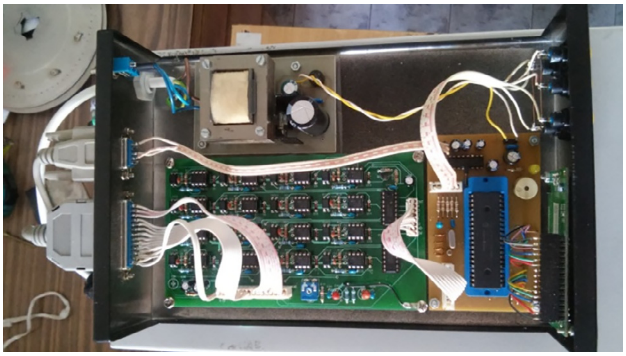

Fig. 3. Internal structure of the control unit.

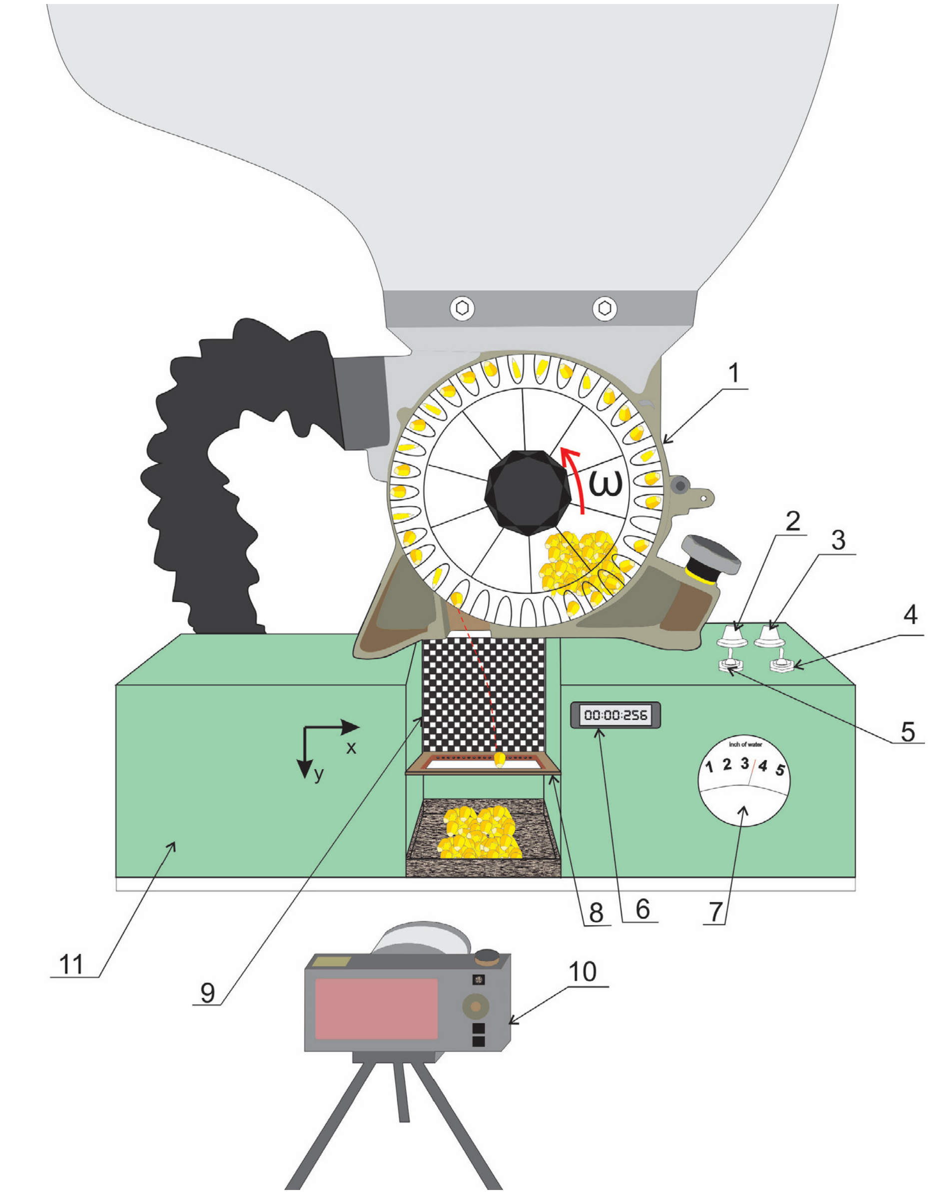

Fig. 4. An overview of verification concept: 1 – seeding mechanism; 2 – regulation of seeding plate revolution speed; 3 – fan speed regulation; 4 – on/off fan; 5 – on/off electric motor; 6 – high precision timer; 7 – analogue pressure gauge; 8 – photo sensor; 9 – background raster plane; 10 – camera; 11 – housing.

2.2.1.3. Method for analyzing the influence of variables on seeding precision. The method of Design of Experiments (DOE) was first used in agricultural studies (Fisher, 1925). The advantage of this method is an inclusion of categorical input factors in the analysis of experimental data as well as the possibilities for determination of influence of not only the input factors but their interactions, too. This is achieved by varying different variables simultaneously and determining their relations by using a multivariable equation.

In this study, full factorial design (Montgomery and Runger, 2011) with four input factors was used (Table 2). Two input factors are categorical: seeding plate (factor A) at two levels and seed variety at seven levels (F1, F2, F3, F4, F5, F6 and F7), and the other two factors are numerical: blowing pressure at two levels and seeding plate revolution speed at four levels (6, 12, 19 and 26 rpm). A total of 112 runs with a combination of all input factors at all levels were performed in a software recommended order with three independent measurements for each run. Five output varieties (responses): standard deviation, coefficient of variation, quality of feed index, multiple and miss indices were observed according to ISO 7256/1. The miss index (*Mi*) is the percentage of spacing greater than 1.5 times the set planting distance (α).

Table 2
List of input factors with their levels.

Input factor	Low	High	Levels
Seeding plate	SP1	SP2	2
Seed variety	F1	F7	7
Blowing pressure (Pa)	254	635	2
Rotational speed of seeding plate (min^{-1})	6	26	4

$$Mi = \frac{N_{miss}}{N_{total}} \times 100$$

where N_{miss} is number of spacing $> 1.5 \times \alpha$; and N_{total} is total number of measured spacing. The multiple index is the percentage of spacing that are less than half of the set plant distance.

$$Mi = \frac{N_{multipe}}{N_{total}} \times 100$$

Table 3
List of observed responses with descriptive statistics.

Response		Min	Max	Mean	Std. Dev.
R1(SD)	St. Dev.	9.52	22.50	16.83	2.72
R2(CV)	Coeff. of var.	5.88	15.25	9.01	1.54
R3(Qfi)	Quality of feed index	3.31	99.02	73.96	23.41
R4(Mu)	Multiple index	0.33	46.05	18.67	12.28
R5(Ms)	Miss index	0	50	7.32	12.49

where $N_{multiple}$ is number of spacing $< 0.5 \times \alpha$. Basic parameters of descriptive statistics (mean, minimal and maximal value and standard deviations) for all responses are given in Table 3. In order to stabilize the response variance and making the distribution of the response variable closer to the normal distribution the transformation of the response is used (Montgomery, 2001). Transformations often have little effect when the ratio of maximal and minimal values of observed response is less than 2 or 3, while ratio greater than 10 usually indicates that transformation is needed. For selecting a variance-stability transformation in current study the Box-Cox Method is used. It is suggested square root transformation for multiple index and logarithmic transformation for miss index. The normal plot of the residuals and the residuals versus predicted response values plot are used to test normality and homogeneity of variances assumptions, respectively.

The method of analysis of variance (ANOVA) was used to determine the significance of influence of input (main) factors and the interactions of two of them (2fi). ANOVA tables (consisting of sum of squares (SS), degree of freedom (dF), mean square error (MSE), F-values and p-values for main factors and 2fi) are given for all responses. Factors with p-value less than 0.05 are marked as statistically significant.

DOE was employed for multiple regression analyses using experimental data from all responses, where models consisted of 10 terms: main (A, B, C, D) and 2fi (AB, AC, AD, BC, BD, CD). The direction and strength of impacts of main factors on the responses are presented on the graphs, where the fixed factor was taken to be the average of all combinations of the rest input factors. Adequacy of the obtained models was checked by using residual analysis which analyzed the following: normal plot of residuals, residuals vs. predicted plot, and predicted vs. actual plot which are all given in the supplement material (Graphs S1, S2, S3 and S4).

Optimization of the output parameters was performed using the obtained model within the studied experimental range of input parameters. The minimization of standard deviation, variation, miss index, multiple index and maximization of quality of feed index were required (Table 4). Condition for quality of feed index had the highest importance, while the multiple index was assigned with the lowest importance. Desirability function was used as the indicator of fulfillment of given conditions. All calculations were performed by Design-Expert 10 and Statistica 12 software.

Table 4
Initial criteria for optimization.

Name	Goal	Lower limit	Upper limit	Importance
Seeding plate	in range	SP1	SP2	3
Seed variety	in range	F1	F7	3
Blowing pressure (Pa)	in range	254	635	3
Rotational speed of seeding plate (min^{-1})	in range	6	26	3
St. Dev.	minimize	9.52	22.5	3
Coef. of Var.	minimize	5.87	15.24	3
Given distance	maximize	3.3	99	5
Double	minimize	0.33	46	1
Empty	minimize	0	50	3

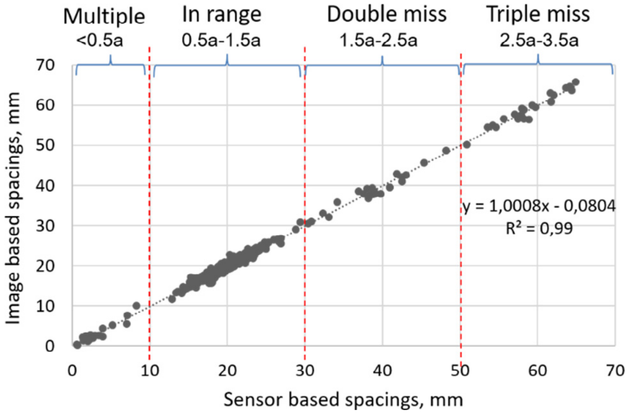

Fig. 5. Comparison of seed spacings measured with photo-electronic system and camera system during validation process.

3. Results and discussion

To assess the reliability of a photoelectric sensor device, the comparison was done between photoelectric sensor data and image-based data (Fig. 5) for the given planter configuration at 6, 12, 19 and 26 rpm of seeding plate and all test runs. The presented results revealed insignificant deviation of each photoelectric seed spacing value and seed spacing obtained using the image-based data. The obtained model describes a strong linear connection ($R^2 = 0.99$), so the photo-electronic system worked well in obtaining the seed spacing data. Also, the system showed the same reliability in detecting multiple seed and miss seed. These results indicated that the photo-element distance of 5 mm on the optical sensor did not affect the measurement accuracy in the case of corn seed detection. However this does not exclude the possibility of occurrence of errors when detecting other seed types. There is probability that the seeds with diameter less than 3 mm, in certain circumstances and position relative to the sensor, will not sufficiently overshadow the photo-receiving diodes and will cause more frequent omissions. From that aspect, it would be desirable to repeat the testing with other types of seeds in order to determine real possibilities of the device. During the test, 3 seeds were not detected, which could be explained by possible simultaneous passing of two consecutive seeds in a very short time, or by simultaneous shading of more diodes by two consecutive seeds that were not recognized by the system. If two seeds are held by a single cell on the seeding plate, and if their free fall path matches, their mutual distance will be minimal, and only one shadow will be registered on the sensor, which will produce a wrong reading. This conclusion indicates that with the increase in the frequency of multiple seed appearance the occurrence of the mentioned error increases. The contribution of undetected seeds in the total population of data was negligible and it did not hinder the subsequent analysis. The performances of the electronic device met the criteria of the validation process and it was used in further studying of the influence of observed parameters on the seeding distribution accuracy.

Comprehensive analysis of the impacts of all variables (seeding plate, seed variety, blowing pressure and rotational speed of seeding plate) on seed spacing uniformity was expressed with Coefficient of Variation (CV), Quality of feed index (QFi), Miss index (Ms) and Multiple index (Mu) and presented in the text below. Standard deviation was not recorded due to the correspondence with parameter CV. Based on the ANOVA results (Table 5) it was concluded that input factors such as seed variety ($p < 0.05$) and rotational speed of the seeding plate had a statistically significant influence ($p < 0.0001$) on CV. Rotational speed of the seeding plate had the strongest influence on seed spacing dispersion which is clearly evident from the inclination angle at Fig. 6a. It positively correlated with CV which is common for all types of seeding mechanisms, considering the previous results of

Table 5
ANOVA table for CV.

St. dev.	SS	df	MSE	F-value	p-value
Model	527.38	48	10.99	2.4	0.0006
A-A	0.94	1	0.94	0.21	0.652
B-B	78.86	6	13.14	2.87	0.0154
C-C	2.49	1	2.49	0.54	0.464
D-D	202.78	3	67.59	14.77	< 0.0001
AB	57.38	6	9.56	2.09	0.067
AC	0.021	1	0.021	0.005	0.946
AD	29.14	3	9.71	2.12	0.106
BC	4.43	6	0.74	0.16	0.986
BD	130.1	18	7.23	1.58	0.094
CD	21.23	3	7.08	1.55	0.211
Residual	288.25	63	4.58		
Cor Total	815.62	111			

Note: A-seeding plate; B-seed variety; C-Blowing pressure and C-Rotational speed of seeding plate.

other authors. It means that 6 rpm of seeding plate gave the smallest seed spacing deviation (CV = 10.67%), while the seeding plate speed of 26 rpm caused a significantly higher value of CV (36.97%). The speeds from 6 to 12 rpm on the chart show a steeper slope compared to the range from 12 to 26 rpm, which indicates a declining influence as speed increased. In real field conditions, the rotational speed of a seeding plate is in direct relation with seeder ground velocity, hence its influence on seeding quality is stronger due to possible seed moving and bouncing in the open furrow. In our case of laboratory testing, it is highly possible that the increased velocity of seeding plate intensified the trajectory distortion of falling seeds due to greater differences in initial impulses between two consecutive seeds and an emphasized difference of air resistance influence on seed falling range.

It is difficult to determine the level of influence of seed varieties on CV outcomes in Fig. 6a; however, Table 5 clearly shows that the seed varieties parameter affected the CV value and it also had significant interaction with the parameters of type of seeding plate and intensity of rotational speed of seeding plate. The best performance was obtained with F-5 seed variety (CV = 19.4%) that corresponds to its high degree of sphericity (82%). Other varieties were in a narrow range of 23.4–26.5% which indicates low reaction of the CV parameter. In that sense, it should be noted that each seed had a specific shape and took an unpredictable position within the seeding plate cell (opening), which certainly affected the initial seed kinematics at the ejection moment as described earlier. Thus, the shape and size of the seeding plate holes can

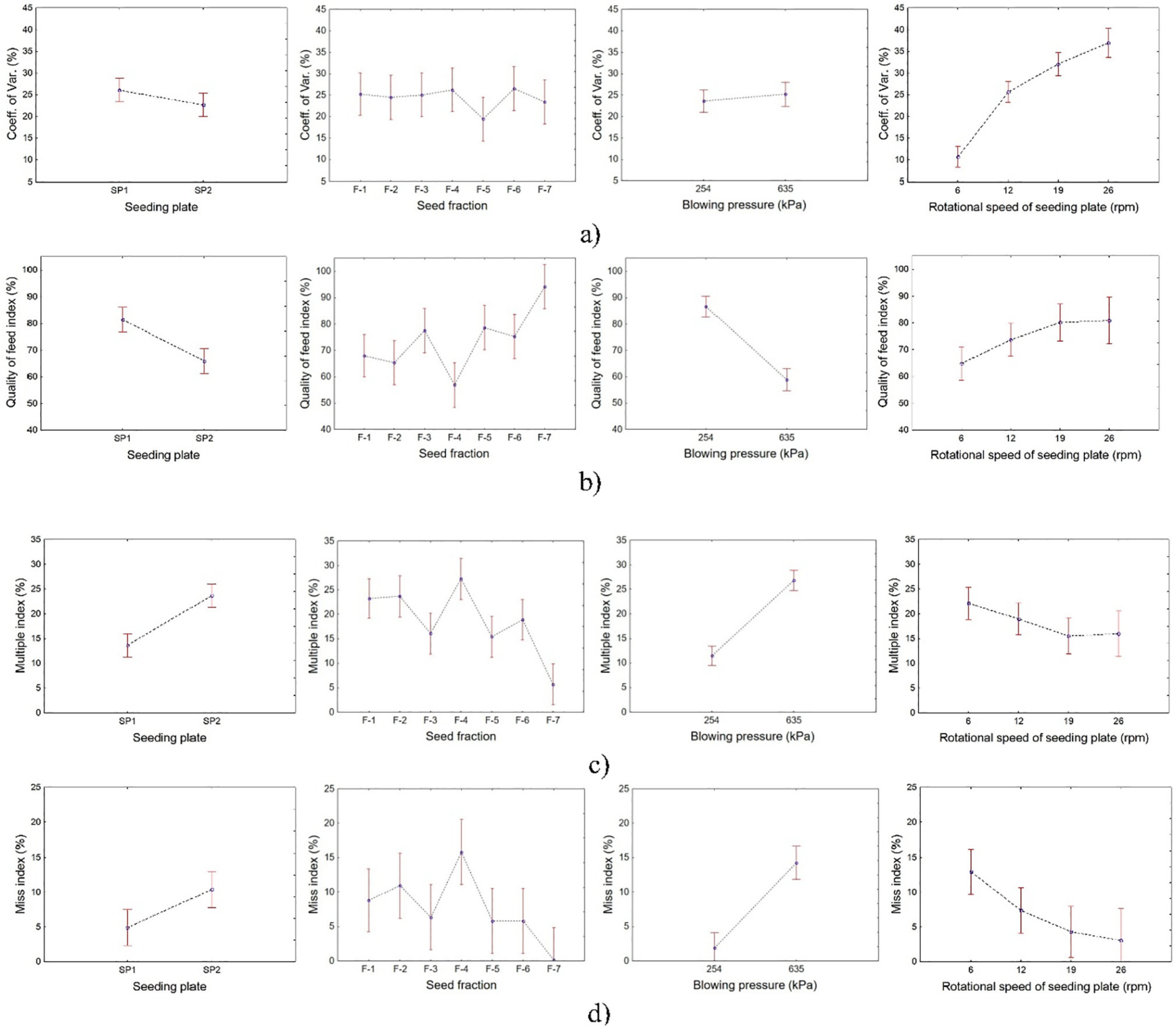

Fig. 6. Effects of variables on calculated parameters of Coeff. of Var. (a), Quality of feed index (b), Multiple index (c), Miss index (d).

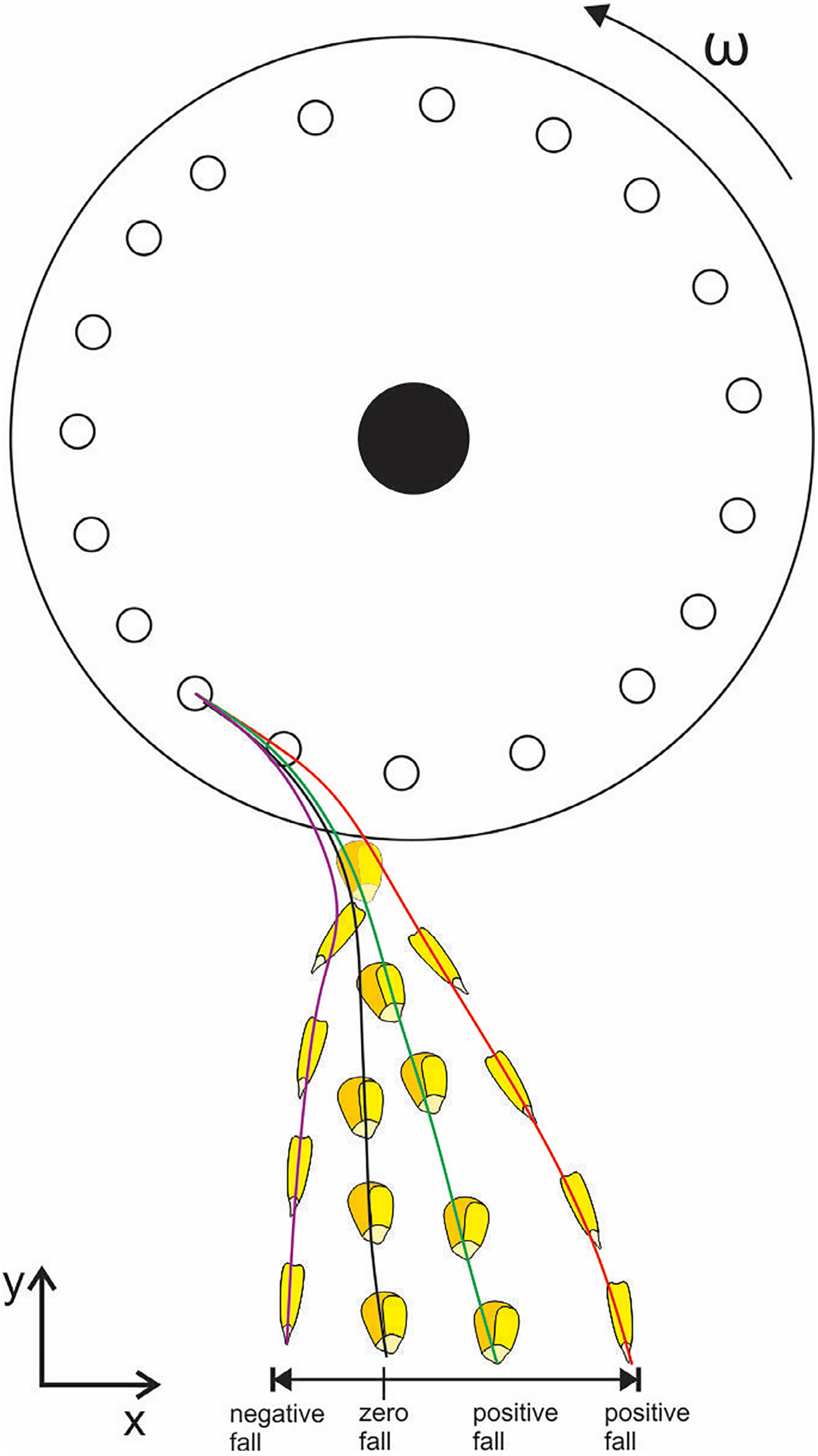

Fig. 7. Observed seed trajectories during validation test with image recording technique.

increase or decrease the seed shape effect on the precision of seeding (Table 4, p = 0.067). In general, variations of seed spacing for all seed varieties were not statistically significant for p = 0.05, but in case of seed variety F-5, there was significant difference in relation to other varieties that were used in the test. By visual inspection (frame by frame), during the validation process of the electronic device, higher deviations of the flat seed path were detected due to the greater influence of aerodynamics and air resistance, which was not the case with

Table 6
ANOVA table for quality of feed.

	SS	df	MSE	F-value	p-value
Model	52901.81	48	1102.12	8.2	< 0.0001
A-A	6309	1	6309	46.96	< 0.0001
B-B	12965.22	6	2160.87	16.08	< 0.0001
C-C	19047.79	1	19047.79	141.77	< 0.0001
D-D	3881.8	3	1293.93	9.63	< 0.0001
AB	1100.81	6	183.47	1.37	0.2424
AC	869.14	1	869.14	6.47	0.0134
AD	420.74	3	140.25	1.04	0.3794
BC	4354.84	6	725.81	5.4	0.0001
BD	2307.48	18	128.19	0.95	0.5209
CD	1645	3	548.33	4.08	0.0103
Residual	8464.38	63	134.36		
Cor Total	61366.2	111			

Table 7
ANOVA table for multiple index.

	SS	df	MSE	F-value	p-value
Model	260.88	48	5.44	16.5	< 0.0001
A-A	50.69	1	50.69	153.89	< 0.0001
B-B	87.51	6	14.58	44.28	< 0.0001
C-C	100.41	1	100.41	304.83	< 0.0001
D-D	6.19	3	2.06	6.27	0.0009
AB	1.06	6	0.18	0.54	0.7781
AC	2.82	1	2.82	8.57	0.0048
AD	0.12	3	0.039	0.12	0.9496
BC	6.32	6	1.05	3.2	0.0083
BD	5.66	18	0.31	0.95	0.52
CD	0.097	3	0.032	0.098	0.961
Residual	20.75	63	0.33		
Cor Total	281.63	111			

round seeds (Fig. 7). This statement supports the results of seeding quality given in Fig. 6 where it is evident the lowest seeding quality for variety F-4 which has the lowest sphericity (0.67%) and second smallest mass of 1000 seeds (233 g, Table 1).

Thus, a portion of flat seeds in a given variety probably contributed to an increased deviation from the given distance. Changes of rotational speed of seeding plate resulted in the highest differences of CV between data groups. Also, the interactions of AB (seeding plate and seed variety) had a noticeable effect on CV. Seeding plate SP1 contributed to higher variation in seed spacing compared to SP2, but it did not show significant influence on the seeding precision, as with the blowing pressure parameter.

In case of Quality of feed index parameter, all main factors had a statistically significant influence ($p < 0.0001$, ANOVA, Table 6). AC, BC and CD (2fi of factor C with all other factors) are the interactions specified as significant. The highest influence was recorded with blowing pressure (Fig. 6b) factor and seed varieties factor, followed by rotational speed of the seeding plate and type of seeding plate. The blowing pressure value is crucial for seed catching and holding during the transportation process by the seeding mechanism. If the air pressure is not well adjusted for a specific type of a seeding device, problems such as more misses or multiple seed in the seeding may occur. Lower air pressure gave significantly better results with 86.6% seed spacing in range compared to higher air pressure with only 58.4% seed spacing in range. Also, the seed variety was the second most influencing factor, which indicated the importance effect of seed shape on seeding performance. Seed variety F-7 had the best response in all test combinations regarding the parameter of feed index quality (QFi = 94.1%). This could be explained with the fact that variety

F-7 distinguishes itself from others in all presented descriptors. In general, shape observation showed F-7 seeds as largest and heaviest (Table 1) which follows earlier statement. Seeding plate SP1 achieved better results in seeding performance (QFi = 81.4%) than SP2 (QFi = 65.8%), although that parameter had the lowest impact on the Quality of feed index in comparison to other test variables. The parameter of seeding plate rotational speed seems to fit linearly (within the range of 6–19 rpm) with quality of feed index, but the obtained differences were not highly significant. As the rotational speed increased, the quality of feed index also increased up to 80.92%. The rotational speeds of seeding plate, 19 rpm and 26 rpm, gave almost the same values of QFi. This phenomenon could be the result of intensive seed mixing at a higher seeding plate rotational speed. This caused the blowing air to pass through empty space between the seeds with lower resistance, thus reducing the internal friction and seed-by-seed ejection before the ejection point. The second reason is a higher centrifugal force which is an important factor of good seed holding in this type of seeding plate with the seeding plate holes externally positioned. The strongest combination of influences of different factors on Quality of Feed index was recorded with seed variety and blowing pressure. The interactions between seeding plate and blowing pressure, as well as between the blowing pressure and rotational speed of seeding plate, had similar effects on Quality of feed index. An obvious conclusion can be drawn here: the blowing pressure had a major impact on the variation of quality of feed index due to its single acting influence as well as its contribution in dual acting.

Similarly to Quality of feed index, all the main factors had a statistically significant influence on Multiple index variations with the same order of factor impact (Table 7). Again, the blowing pressure and seed variety had a very strong influence on the frequency of multiple seeding occurrences (Fig. 6c). Air pressure of 254 kPa proved to be more acceptable than 635 kPa due to a much lower number of multiple seed. It could be explained as follows: higher air pressure caused stronger seed-to-plate connection and complicated the process of cleaning excessive seeds during seeding plate rotation which could influence more multiple seed. The ANOVA test confirmed that the increase in air pressure, in general, produced more multiples (26.8%) than lower air pressure (11.5%). The opposite situation was recorded in case of rotational speed of seeding plate. Seeding plate rotational speeds of 19 rpm and 26 rpm showed almost the same results (around 15%) with respect to the number of misses. However, the speeds of 6 rpm and 12 rpm resulted in the number of misses being significantly higher (up to 22%). Seed variety proved to be one very important factor when it came to seeding multiple seeds. Flat seeds are probably more difficult for the seeding mechanism to single out than the round seeds because of greater possibility for multiple seeds to stack together in one seeding plate hole. In that sense, the results indicated different levels of influence of each seed variety on the number of multiples. As Fig. 6c shows, the relation of seed varieties with multiple index cannot be described with adequate function due to the fluctuation of results. Variety F-7 stands out with the lowest amount of multiples (5.65%) of total recorded spacing. In this test, seeding plate SP1 had better efficiency than SP2 because it produced a significantly lower average number of multiple seeds occurrence (13.63%). Based on Table 7, a significant influence of combined factors AC and BC on multiple index can be observed. Again, the blowing pressure factor figures in both interaction combinations, which proves its high contribution to Multiple index value.

The A, B, C, D factors and interactions AC, BC showed statistically significant influences on the Miss index (Table 8). According to Fig. 6d and mentioned interactions it follows that factor C had the highest influence, followed by factors B, D and A. Air pressure of 254 kPa caused statistically significant lower number of misses (1.4%) than air pressure of 635 kPa (14.6%). More air pressure produced stronger blowing air stream through the seeding plate holes which could affect turbulent air motion and consequently the vibration of seeds and bad seed holding. The tests with SP1 showed only 4.9% of spacing fell in range of expected spacing, but with SP2 it was more than twice, in general. It could be stated that the seeding plate SP2 was not properly shaped for the used seed varieties so it caused seeds falling back before reaching the

Table 8
ANOVA table for miss index.

	SS	df	MSE	F-value	p-value
Model	39.71	48	0.83	4.35	< 0.0001
A-A	1.28	1	1.28	6.72	0.0119
B-B	10.27	6	1.71	9	< 0.0001
C-C	12.86	1	12.86	67.58	< 0.0001
D-D	2.78	3	0.93	4.86	0.0042
AB	1.84	6	0.31	1.61	0.1592
AC	2.76	1	2.76	14.53	0.0003
AD	0.068	3	0.023	0.12	0.9487
BC	4.58	6	0.76	4.01	0.0018
BD	2.32	18	0.13	0.68	0.8195
CD	0.96	3	0.32	1.68	0.18
Residual	11.98	63	0.19		
Cor Total	51.69	111			

ejection point. Again, variety F-7 had the best seeding results from the aspect of seeding reliability because this variety had the smallest average number of misses (only 0.12%), while the worst results were achieved with variety F-4 (15.4% of misses). The mentioned differences in the share of misses in all recorded spacings suggest that the seed shape is largely responsible for the obtained plant population in the field. It is a crucial component of profitable cropping compared to other aspects of seeding quality. By comparing Fig. 6b and c, similar charts can be observed for the miss and multiple index parameters. This implies that the measuring system is highly reliable for generating data on seed spacing, and that the conducted tests were properly designed. As Fig. 6d shows, the focus should be on air pressure adjustment and seed variety selection. A negative correlation was obtained between the miss index and rotational speed of the seeding plate. When the seeding plate speed increases, the number of misses declines, hence the lowest frequency of misses was detected with 26 rpm seeding plate speed (3.0%) and the highest with 6 rpm seeding plate speed (12.9%). Air pressure intensity, except its single influence on miss index also showed a significant mutual influence with seeding plate and seed variety factors, which confirms the previous statements.

As it can be seen from this research, all variables contributed to each of the observed parameters of seeding quality. Since there were several levels (2–7) according to which the variables were varied in all possible combinations, a large amount of data was obtained in order to fully understand the performance of the seeding mechanism. Standard statistical methods were not satisfactory for drawing a conclusion about the most suitable combination of variables that could provide the best seeding performance according to the defined criteria. In that sense, for multifactorial experiments, the optimization techniques are quite suitable and have been successfully used in other fields of research. Due to the seeding requirements, conditions with importance are given for each seeding quality parameter (Table 4). Results of optimization are listed in Table 9. It should be noted that the optimization criteria are adjustable and can be aligned with the desired goals. The required conditions are met with high values of desirability function (0.764–0.878). According to Table 9, we can propose the types and values of the observed seeding parameters that gave the best results in the optimization process. Seeding plate SP1 and lower blowing pressure (254 kPa) almost always gave good results regardless of other settings. Seed varieties F-7 and F-5 proved to be equally good for seeding, but we cannot single out one appropriate rotational speed of the seeding plate due to the versatile arrangement of its interactions with other seeding parameters. The highest desirability was achieved with the seeding plate SP1, variety F7, blowing pressure 254 kPa and rotational speed of seeding plate 19 rpm with response values: CV = 7.21%, QFi = 98.66%, Multiple index = 0.33% and Miss index = 0.15%. Another benefit of this approach is the choice of a combination of input parameters that are easy or inexpensive for setting minimal negative consequences on the seeding quality, which could be important from a practical point of view. This example shows that the DOE method is a very helpful method for discovering the best seed drill adjustment and seed variety selection, which is the key element for having high yields of the desired plant population. This approach to data analysis provides insight to all parameters and their effects on the seeding efficiency. Furthermore, the method has been proven to be successful in the application with given data with wider possibilities considering the range of variables and expected results. These kinds of calculations should be incorporated in the software protocols of existing electronic systems for rapid laboratory assessment of a seeding mechanism which can significantly upgrade their utilization and usability in order to instantly offer a solution for the best possible settings. Some of these options as well could be used in commercial electronic control devices which are embedded on seed drills.

4. Conclusion

Data validation tests confirmed a high level of confidence of measured seed distance ($R^2 = 0.99$). The tested photo-electronic system was unable to detect multiple seeds when the seeds passed simultaneously through the sensor zone, not detecting the difference between seeds and particles which were suspended in a certain percentage. The sensitivity of the optical sensor must be properly adjusted to avoid a fault reading induced by external light source reflections (sunlight or ambient light).

It was determined that the revolution speed of the seeding plate ($p = 0.0001$) had the most significant effect on the deviation of the distance between the seeds, followed by the seed varieties ($p = 0.01$). The air pressure and seed variety factors were recognized as the most influential on the quality of the feed index, while the pressure factor of the air flow and the variety of the seed were the most influential factors on the occurrence of miss and multiple seed. Frame by frame analysis of high-speed recordings, indicated that there was a significant influence of air resistance and aerodynamics of the seed on seed trajectory divergency especially in the case of flat seeds. This aspect should be studied in future research. For the tested seeding device and the defined optimization criteria the best result was achieved with seeding plate

Table 9
Results of optimization for given levels of importance.

No.	A	B	C	D	St. Dev.	CV	QFi	Multiple index	Miss index	Desirability
1	SP1	F7	254	19	14.07	7.21	98.66	0.33	0.15	0.88
2	SP1	F5	254	12	13.56	7.16	93.49	2.21	0.14	0.87
3	SP1	F7	254	12	13.95	7.10	95.61	0.54	0.39	0.86
4	SP1	F5	254	6	13.79	7.53	91.97	3.23	0.23	0.84
5	SP1	F7	254	26	16.53	8.14	99.74	0.17	0.21	0.80
6	SP2	F7	635	12	13.90	7.35	86.07	11.83	0.44	0.79
7	SP1	F5	254	26	17.10	8.56	97.61	1.34	0.01	0.78
8	SP1	F1	254	6	13.98	7.71	84.09	12.00	0.60	0.77
9	SP1	F7	254	6	16.41	8.35	94.09	1.09	0.51	0.77
10	SP1	F4	254	6	14.13	7.82	86.89	13.07	0.75	0.76

SP1, the highest sphericity with variety (F7), and the lowest blowing pressure and rotational speed of 19 rpm.

Obtained results provide valuable information for producers which seed shape and seeding mechanism regime ensure the best seeding outcomes. According to site-specific field management trends, detection of seed fall with detection of passing time and relative location between consecutive seeds simultaneously with geopositioning could be used for creation of an accurate seeded seed map for purpose of inter-row and intra-row weeding, local application of nutrients and pesticides for subsequent individual crop plant care activities.

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