

## Assessment of the Behaviour of Potatoes in a Cup-belt Planter

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The functioning of most potato planters is based on transport and placement of the seed potatoes by a cup-belt. The capacity of this process is rather low when planting accuracy has to stay at acceptable levels. The main limitations are set by the speed of the cup-belt and the number and positioning of the cups. It was hypothesised that the inaccuracy in planting distance, that is the deviation from uniform planting distances, mainly is created by the construction of the cup-belt planter.

To determine the origin of the deviations in uniformity of placement of the potatoes a theoretical model was built. The model calculates the time interval between each successive potato touching the ground. Referring to the results of the model, two hypotheses were posed, one with respect to the effect of belt speed, and one with respect to the influence of potato shape. A planter unit was installed in a laboratory to test these two hypotheses. A high-speed camera was used to measure the time interval between each successive potato just before they reach the soil surface and to visualise the behaviour of the potato.

The results showed that: (a) the higher the speed of the cup-belt, the more uniform is the deposition of the potatoes; and (b) a more regular potato shape did not result in a higher planting accuracy.

Major improvements can be achieved by reducing the opening time at the bottom of the duct and by improving the design of the cups and its position relative to the duct. This will allow more room for changes in the cup-belt speeds while keeping a high planting accuracy.

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### 1. Introduction

The cup-belt planter (*Fig. 1*) is the most commonly used machine to plant potatoes. The seed potatoes are transferred from a hopper to the conveyor belt with cups sized to hold one tuber. This belt moves upwards to lift the potatoes out of the hopper and turns over the upper sheave. At this point, the potatoes fall on the back of the next cup and are confined in a sheet-metal duct. At the bottom, the belt turns over the roller, creating the opening for dropping the potato into a furrow in the soil.

Capacity and accuracy of plant spacing are the main parameters of machine performance. High accuracy of plant spacing results in high yield and a uniform sorting

of the tubers at harvest (McPhee *et al.*, 1996; Pavek & Thornton, 2003). Field measurements (unpublished data) of planting distance in The Netherlands revealed a coefficient of variation (CV) of around 20%. Earlier studies in Canada and the USA showed even higher CVs of up to 69% (Misener, 1982; Entz & LaCroix, 1983; Siczka *et al.*, 1986), indicating that the accuracy is low compared to precision planters for beet or maize.

Travelling speed and accuracy of planting show an inverse correlation. Therefore, the present cup-belt planters are equipped with two parallel rows of cups per belt instead of one. Doubling the cup row allows double the travel speed without increasing the belt speed and thus, a higher capacity at the same accuracy is expected.

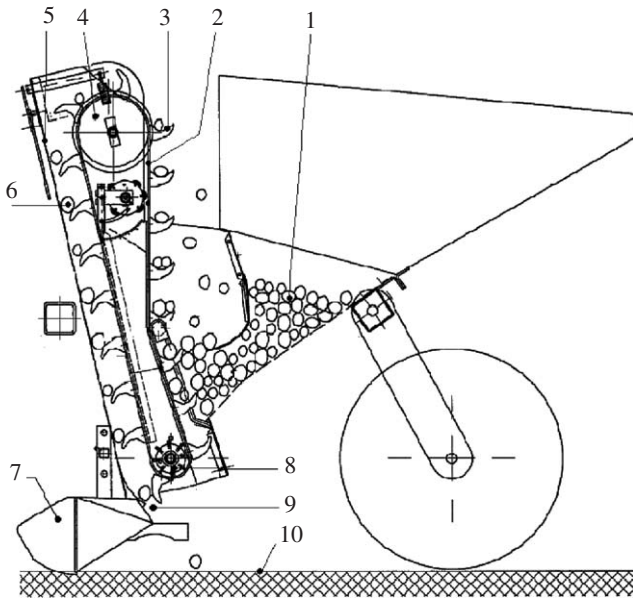


Fig. 1. Working components of the cup-belt planter: (1) potatoes in hopper; (2) cup-belt; (3) cup; (4) upper sheave; (5) duct; (6) potato on back of cup; (7) furrower; (8) roller; (9) release opening; (10) ground level

The objective of this study was to investigate the reasons for the low accuracy of cup-belt planters and to use this knowledge to derive recommendations for design modifications, *e.g.* in belt speeds or shape and number of cups.

For better understanding, a model was developed, describing the potato movement from the moment the potato enters the duct up to the moment it touches the ground. Thus, the behaviour of the potato at the bottom of the soil furrow was not taken into account. As physical properties strongly influence the efficiency of agricultural equipment (Kutzbach, 1989), the shape of the potatoes was also considered in the model.

Two null hypotheses were formulated: (1) the planting accuracy is not related to the speed of the cup-belt; and (2) the planting accuracy is not related to the dimensions (expressed by a shape factor) of the potatoes. The hypotheses were tested both theoretically with the model and empirically in the laboratory.

## 2. Materials and methods

### 2.1. Plant material

Seed potatoes of the cultivars (cv.) Sante, Arinda and Marfona have been used for testing the cup-belt planter, because they show different shape characteristics. The shape of the potato tuber is an important characteristic

for handling and transporting. Many shape features, usually combined with size measurements, can be distinguished (Du & Sun, 2004; Tao *et al.*, 1995; Zödler, 1969). In the Netherlands grading of potatoes is mostly done by using the square mesh size (Koning *de et al.*, 1994), which is determined only by the width and height (largest and least breadth) of the potato. For the transport processes inside the planter, the length of the potato is a decisive factor as well.

A shape factor  $S$  based on all three dimensions was introduced:

$$S = 100 \frac{l^2}{wh} \quad (1)$$

where  $l$  is the length,  $w$  the width and  $h$  the height of the potato in mm, with  $h < w < l$ . As a reference, also spherical golf balls (with about the same density as potatoes), representing a shape factor  $S$  of 100 were used. Shape characteristics of the potatoes used in this study are given in Table 1.

### 2.2. Mathematical model of the process

A mathematical model was built to predict planting accuracy and planting capacity of the cup-belt planter. The model took into consideration radius and speed of the roller, the dimensions and spacing of the cups, their positioning with respect to the duct wall and the height of the planter above the soil surface (Fig. 2). It was assumed that the potatoes did not move relative to the cup or rotate during their downward movement.

The field speed and cup-belt speed can be set to achieve the aimed plant spacing. The frequency  $f_{pot}$  of potatoes leaving the duct at the bottom is calculated as

$$f_{pot} = \frac{v_c}{x_c} \quad (2)$$

where  $v_c$  is the cup-belt speed in  $\text{ms}^{-1}$  and  $x_c$  is the distance in m between the cups on the belt. The angular speed of the roller  $\omega_r$  in  $\text{rad s}^{-1}$  with radius  $r_r$  in m is calculated as

$$\omega_r = \frac{v_c}{r_r} \quad (3)$$

**Table 1**  
Shape characteristics of potato cultivars and golf balls used in the experiments

Cultivar	Square mesh size, mm	Shape factor
Sante	28–35	146
Arinda	35–45	362
Marfona	35–45	168
Golf balls	42.8	100

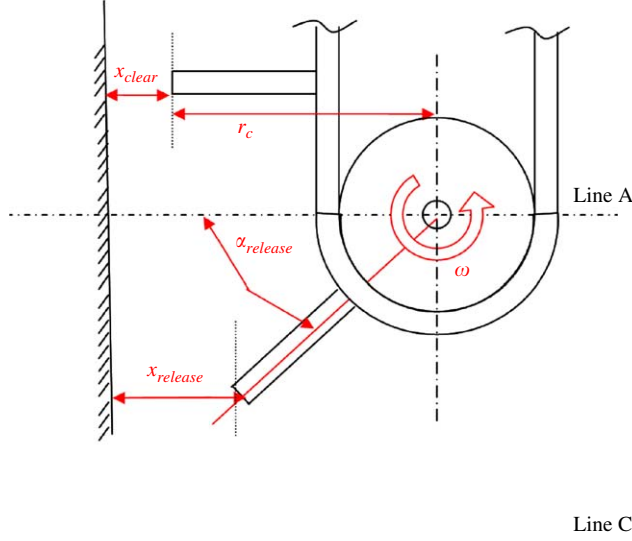


Fig. 2. Process simulated by model, simulation starting when the cup crosses line A; release time represents time needed to create an opening sufficiently large for a potato to pass; model also calculates time between release of the potato and the moment it reaches the soil surface (free fall);  $r_c$ , sum of the radius of the roller, thickness of the belt and length of the cup;  $x_{clear}$ , clearance between cup and duct wall;  $x_{release}$ , release clearance;  $\alpha_{release}$ , release angle;  $\omega$ , angular speed of roller; line C, ground level, end of simulation

The gap in the duct has to be large enough for a potato to pass and be released. This gap  $x_{release}$  in m is reached at a certain angle  $\alpha_{release}$  in rad of a cup passing the roller. This release angle  $\alpha_{release}$  (Fig. 2) is calculated as

$$\cos \alpha_{release} = \frac{r_c + x_{clear} - x_{release}}{r_c} \quad (4)$$

where:  $r_c$  is the sum in m of the radius of the roller, the thickness of the belt and the length of the cup; and  $x_{clear}$  is the clearance in m between the tip of the cup and the wall of the duct.

When the parameters of the potatoes are known, the angle required for releasing a potato can be calculated. Apart from its shape and size, the position of the potato on the back of the cup is determinative. Therefore, the model distinguishes two positions: (a) minimum required gap, equal to the height of a potato; and (b) maximum required gap equal to the length of a potato.

The time  $t_{release}$  in s needed to form a release angle  $\alpha_0$  is calculated as

$$t_{release} = \frac{\alpha_{release}}{\omega_r} \quad (5)$$

Calculating  $t_{release}$  for different potatoes and possible positions on the cup yields the deviation from the average time interval between consecutive potatoes. Combined with the duration of the free fall and the field speed of the planter, this gives the planting accuracy.

When the potato is released, it falls towards the soil surface. As each potato is released on a unique angular position, it also has a unique height above the soil surface at that moment (Fig. 2). A small potato will be released earlier and thus at a higher point than a large one.

The model calculates the velocity of the potato just before it hits the soil surface  $v_{end}$  in  $\text{m s}^{-1}$ . The initial vertical velocity of the potato  $v_0$  in  $\text{m s}^{-1}$  is assumed to equal the vertical component of the track speed of the tip of the cup:

$$v_0 = r_c \omega_r \cos \alpha_{release} \quad (6)$$

The release height  $y_{release}$  in m is calculated as

$$y_{release} = y_r - r_c \sin \alpha_{release} \quad (7)$$

where  $y_r$  in m is the distance between the centre of the roller (line A in Fig. 2) and the soil surface.

The time of free fall  $t_{fall}$  in s is calculated with

$$y_{release} = v_{end} t_{fall} + 0.5 g t_{fall}^2 \quad (8)$$

where  $g$  is the gravitational acceleration ( $9.8 \text{ m s}^{-2}$ ) and the final velocity  $v_{end}$  is calculated as

$$v_{end} = v_0 + 2 g y_{release} \quad (9)$$

with  $v_0$  in  $\text{m s}^{-1}$  being the vertical downward speed of the potato at the moment of release.

The time for the potato to move from Line A to the release point  $t_{release}$  has to be added to  $t_{fall}$ .

The model calculates the time interval between two consecutive potatoes that may be positioned in different ways on the cups. The largest deviations in intervals will occur when a potato positioned lengthwise is followed by one positioned heightwise, and *vice versa*.

### 2.3. The laboratory arrangement

A standard planter unit (Miedema Hassia SL 4(6)) was modified by replacing part of the bottom end of the sheet metal duct with similarly shaped transparent acrylic material (Fig. 3). The cup-belt was driven *via* the roller (8 in Fig. 1), by a variable speed electric motor. The speed was measured with an infrared revolution meter. Only one row of cups was observed in this arrangement.

A high-speed video camera (SpeedCam Pro, Weinberger AG, Dietikon, Switzerland) was used to visualise the behaviour of the potatoes in the transparent duct and to measure the time interval between consecutive potatoes. A sheet with a coordinate system was placed behind the opening of the duct, the X axis representing the ground level. Time was registered when the midpoint of a potato passed the ground line. Standard deviation

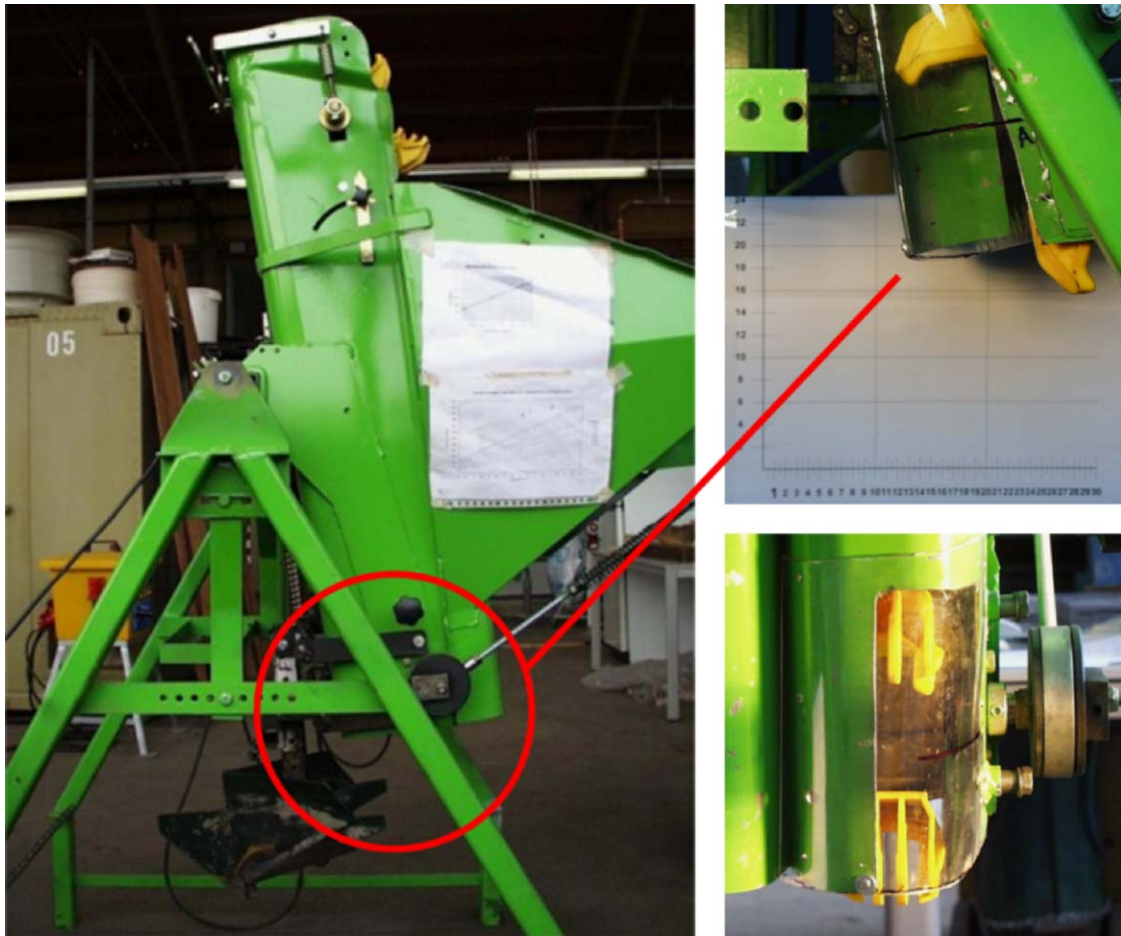


Fig. 3. Laboratory test-rig; lower right—part of the bottom end of the sheet metal duct was replaced with transparent acrylic sheet; upper right—segment faced by the high-speed camera

of the time interval between consecutive potatoes was used as measure for plant spacing accuracy.

For the measurements the camera system was set to a recording rate of 1000 frames per second. With an average free fall velocity of  $2.5 \text{ m s}^{-1}$ , the potato moves approx. 2.5 mm between two frames, sufficiently small to allow an accurate placement registration.

The feeding rates for the test of the effect of the speed of the belt were set at 300, 400 and 500 potatoes  $\text{min}^{-1}$  ( $f_{pot} = 5, 6.7$  and  $8.3 \text{ s}^{-1}$ ) corresponding to belt speeds of 0.33, 0.45 and  $0.56 \text{ m s}^{-1}$ . These speeds would be typical for belts with 3, 2 and 1 rows of cups, respectively. A fixed feeding rate of 400 potatoes  $\text{min}^{-1}$  (cup-belt speed of  $0.45 \text{ m s}^{-1}$ ) was used to assess the effect of the potato shape.

For the assessment of a normal distribution of the time intervals, 30 potatoes in five repetitions were used. In the other tests, 20 potatoes in three repetitions were used.

## 2.4. Statistical analysis

The hypotheses were tested using the Fisher test, as analysis showed that populations were normally distributed. The one-sided upper tail Fisher test was used and  $\alpha$  was set to 5% representing the probability of a type 1 error, where a true null hypothesis is incorrectly rejected. The confidence interval is equal to  $(100-\alpha)\%$ .

## 3. Results and discussion

### 3.1. Cup-belt speed

#### 3.1.1. Empirical results

The measured time intervals between consecutive potatoes touching ground showed a normal distribution. Standard deviations  $\sigma$  for feeding rates 300, 400 and 500 potatoes  $\text{min}^{-1}$  were 33.0, 20.5 and 12.7 ms, respectively.

According to the *F*-test the differences between feeding rates were significant. The normal distributions for all three feeding rates are shown in Fig. 4. The accuracy of the planter is increasing with the cup-belt speed, with CVs of 8.6%, 7.1% and 5.5%, respectively.

3.1.2. Results predicted by the model

Figure 5 shows the effect of the belt speed on the time needed to create a certain opening. A linear relationship was found between cup-belt speed and the accuracy of the deposition of the potatoes expressed as deviation from the time interval. The shorter the time needed for creating the opening, the smaller the deviations. Results of these calculations are given in Table 2.

The speed of the cup turning away from the duct wall is important. Instead of a higher belt speed, an increase of the cup's circumferential speed can be achieved by decreasing the radius of the roller. The radius of the roller used in the test is 0.055 m, typical for these planters. It was calculated what the radius of the roller

**Table 2**  
Time intervals between consecutive potatoes calculated by the model (cv. Marfona)

Belt speed, $m\ s^{-1}$	Difference between shortest and longest interval, s
0.72	17.6
0.36	29.4
0.24	42.8

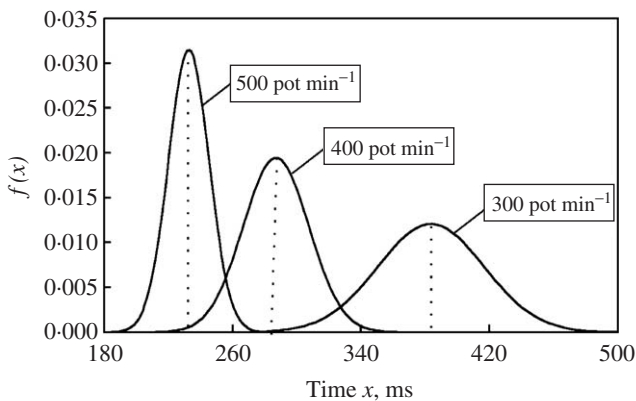


Fig. 4. Normal distribution of the time interval (*x*, in ms) of deposition of the potatoes (*pot*) for three feeding rates

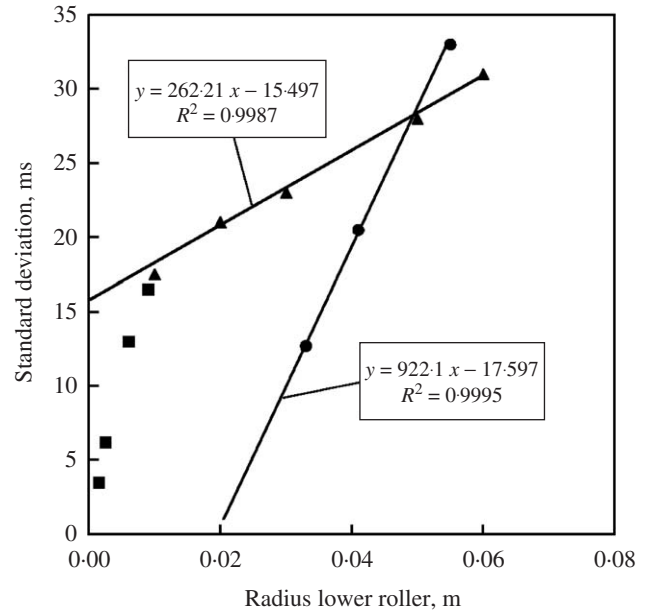


Fig. 6. Relationship between the radius of the roller and the standard deviation of the time interval of deposition of the potatoes; the relationship is linear for radii  $r > 0.01$  m, ●, measurement data; ▲, data from mathematical model; ■, extended for  $r < 0.01$  m; —, linear relationship;  $R^2$ , coefficient of determination

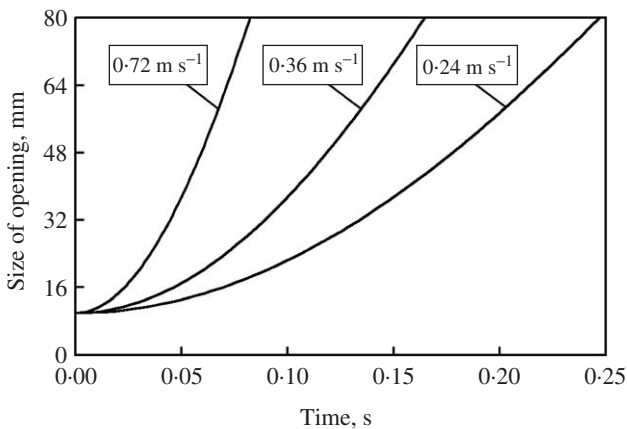


Fig. 5. Effect of belt speed on time needed to create opening

had to be for lower belt speeds, in order to reach the same circumferential speed of the tip of the cup as found for the highest belt speed. This resulted in a radius of 0.025 m for 300 potatoes  $min^{-1}$  and of 0.041 m for 400 potatoes  $min^{-1}$ . Compared to this outcome, a linear trend line based on the results of the laboratory measurements predicts a maximum performance at a radius of around 0.020 m.

The mathematical model [Eqn (5)] predicted a linear relationship between the radius of the roller (for  $r > 0.01$  m) and the accuracy of the deposition of the potatoes. The model was used to estimate standard deviations for different radii at a feeding rate of 300 potatoes  $min^{-1}$ . The results are given in Fig. 6, showing that the model predicts a more gradual decrease in accuracy in comparison with the measured data. A radius of 0.025 m, which is probably the smallest radius technically possible, should have given a decrease in

standard deviation of about 75% compared to the original radius.

### 3.2. Dimension and shape of the potatoes

The results of the laboratory tests are given in Table 3. It shows the standard deviations of the time interval at a fixed feeding rate of 400 potatoes  $\text{min}^{-1}$ . These results were contrary to the expectations that higher standard deviations would be found with increasing shape factors. Especially the poor results of the balls were amazing. The standard deviation of the balls was about 50% higher than the oblong potatoes of cv. Arinda. The normal distribution of the time intervals is shown in Fig. 7. Significant differences were found between the balls and the potatoes. No significant differences were found between the two potato varieties.

The poor performance of the balls was caused by the fact that these balls could be positioned in many ways on the back of the cup. Thus, different positions of the balls in adjacent cups resulted in a lower accuracy of deposition. The three-dimensional drawing of the cup-belt shows the shape of the gap between cup and duct illustrating that different opening sizes are possible (Fig. 8).

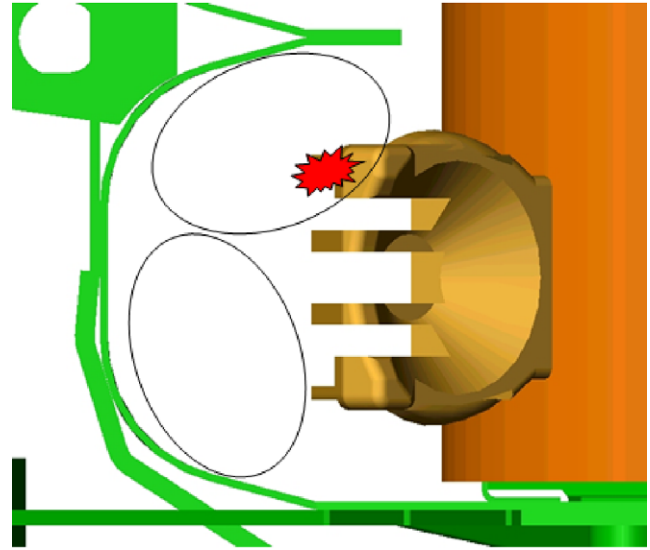


Fig. 8. View from below to the cup at an angle of 45 degrees; position of the potato on the back of the cup is decisive for its release

Arinda tubers were deposited with a higher accuracy than Marfona tubers. Analysis of the recorded frames and the potatoes, demonstrated that the potatoes of cv. Arinda always were positioned with their longest axis parallel to the back of the cup. Thus, apart from the shape factor, a higher ratio width/height will cause a greater deviation. For cv. Arinda, this ratio was 1.09, for cv. Marfona it was 1.15.

**Table 3**  
Effect of cultivars on the accuracy of plant spacing; CV, coefficient of variation

Cultivar	Standard deviation, ms	CV, %
Arinda	8.60	3.0
Marfona	9.92	3.5
Golf balls	13.24	4.6

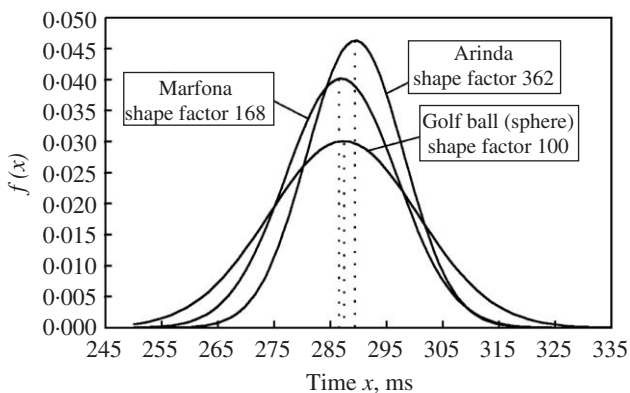


Fig. 7. Normal distribution of the time interval ( $x$ , in ms) of deposition of the potatoes for different shape factors at a fixed feeding rate

### 3.3. Model versus laboratory test-rig

The mathematical model predicted the performance of the process under different circumstances. The model simulated a better performance for spherical balls compared to potatoes whereas the laboratory test showed the opposite. An additional laboratory test was done to check the reliability of the model.

In the model, the time interval between two potatoes is calculated. Starting point is the moment the potato crosses line A and end point is the crossing of line C (Fig. 2). In the laboratory test-rig the time-interval between potatoes moving from line A to C was measured (Fig. 3). The length, width and height of each potato was measured and potatoes were numbered. During the measurement it was determined how each potato was positioned on the cup. This position and the potato dimensions were used as input for the model. The measurements were done at a feeding rate of 400 potatoes  $\text{min}^{-1}$  with potatoes of cv. Arinda and Marfona. The standard deviations of the measured time intervals are shown in Table 4. They were slightly different (higher) from the standard deviations calcu-

**Table 4**  
**Differences between the standard deviations of the opening time measured in the laboratory and calculated by the model**

<i>Cultivar</i>	<i>Shape factor</i>	<i>Standard deviation, ms</i>	
		<i>Measured</i>	<i>Calculated</i>
Arinda	326	8.02	5.22
Marfona	175	6.96	4.40

lated by the model. Explanations for these differences are: (1) the model does not take into consideration situations as shown in *Fig. 8*, (2) the passing moment at line A and C was disputable. Oblong potatoes such as cv. Arinda may fall with the tip or with the longest size down. This may cause up to 6 ms difference for the potato to reach the bottom line C.

#### 4. Conclusions

The mathematical model simulating the movement of the potatoes at the time of their release from the cup-belt was a very useful tool leading to the hypotheses to be tested and to design the laboratory test-rig.

Both the model and the laboratory test showed that the higher the speed of the belt, the more uniform the deposition of the potatoes at zero horizontal velocity. This was due to the fact that the opening, allowing the potato to drop, is created quicker. This leaves less effect of shape of the potato and the positioning of the potato on the cup. A relationship with the belt speed was found. So, to provide more room for reductions in the cup-belt speeds while keeping a high planting accuracy it is recommended to decrease the radius of the roller till as low as technically possible.

This study showed that the accuracy of planting (distance in the seeding furrow) is influenced for a large part by the cup-belt unit of the planter.

A more regular shape (lower shape factor) does not automatically result in a higher accuracy. A sphere (golf ball) in most cases was deposited with a lower accuracy than a potato. This was caused by the shapes of the guiding duct and cups.

It is recommended to redesign the geometry of the cups and duct, and to do this in combination with a smaller roller.

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