

Feed Gate Adaptation of a Spinner Spreader for Uniformity Control

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Variable rate application of fertilisers with traditional spinner-type spreaders is known to suffer from spread pattern uniformity variability as a function of application rate. To demonstrate this variability, simulations using models from the literature were carried out for two cases: (1) a dual disc spreader with segment-type feed gates; and (2) a single disc spreader with conical feed gates. Simulations for the dual disc spreader showed that for higher application rates the pattern becomes ‘M’-shaped, whereas for a single disc spreader the pattern becomes skewed, even though the pattern for low rates was near-Gaussian shaped in both cases.

In this research, an attempt to eliminate the uniformity variability was made, by developing a feed gate control method based on an optical feedback sensor. Simulations showed that the feed gate method is capable of producing high-quality patterns for any given application rate, in both cases, the dual disc spreader with segment-type feed gates, as well as the worst-case scenario being the single disc spreader with conical feed gates.

The performance of the feed gate control method was assessed using data collected from a single disc Lowery 300 spreader. Although the original, uncontrolled pattern of this spreader was of low quality, the adaptive gate control algorithm was capable of producing acceptable patterns around the flow rate of 0.2 kg/s.

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1. Introduction

Environmental impact concerns as well as economic motives have driven site-specific crop management in recent years. A vital part of site-specific crop management is ‘variable rate application’ of materials such as fertilisers. Traditionally, for granular fertiliser application, spinner-type spreaders were used since large areas can be covered effectively, they are simple in design, reliable, inexpensive, robust, and require little maintenance. However, the spinner-type spreader was not intended for variable rate application and was typically calibrated for constant rates. Not surprisingly, the uniformity [expressed in the statistical coefficient of variation (CV) of adjacent overlapped patterns] changes drastically while varying application rates without recalibration. To produce uniform patterns for any application rate, there is a need for a rate- and uniformity-controlled spreader, which does not require calibration.

This paper describes the development of such a controlled spreader. The essential components are: (1) a sensor that provides a spread pattern in real time; (2) feed gates, which allow for control of the flow rate and flow direction; and (3) an algorithm that uses the sensor information to control the application rate and uniformity by adjusting the gates in real time.

The feedback sensor was developed by Grift and Hofstee (1997b). This sensor measures the velocity and diameter of granular particles just after they leave the disc as a function of emanation angle. The velocities and diameters of the particles are then used as inputs for a ballistic model that predicts the landing position of the particles on the ground. The arrangement is capable of predicting the entire spread pattern behind a single disc spreader (Grift & Hofstee, 2002). By using the spread pattern as predicted by the optical sensor, the overall pattern application rate and uniformity can be computed by simulating overlapped patterns for a range of swath widths. The software for predicting the

Notation			
C_D	drag coefficient of a sphere	v_t	tangential particle velocity at the edge of the disc, m/s
d_i	distance of each column from the tram line in the transverse pattern	x	horizontal distance of the particle between the end of the vane and the location during the ballistic flight, m
d_w	weighted arithmetic mean of the single transverse pattern	y	vertical distance of the particle between the disc and the location during the ballistic flight, m
g	gravitational acceleration, m/s ²	β_o	outlet angle of the particle, deg
h	vertical distance from ground to disc, m	μ_v	friction coefficient for particle—vane interaction
K	aerodynamic resistance coefficient, m ⁻¹	μ_d	friction coefficient for particle—disc interaction
m	particle mass, kg	ρ_{AIR}	density of air, kg/m ³
n	number of column vector in the transverse pattern	ρ_p	density of spreading material, kg/m ³
r	distance between particle and disc centre, m	ϕ_b	angle between feed gates, deg
r_b	inner radius of the segment orifice, m	ϕ_d	segment angle of the orifice, deg
r_d	disc radius, m	ϕ_o	position angle of the orifice, deg
r_e	outer radius of the segment orifice, m	ϕ_{o1}	position angle of the orifice 1, deg
r_i	inner radius of a particle area projected on the disc from a feed gate, m	ϕ_{o2}	position angle of the orifice 2, deg
r_p	radius of particle, m	ϕ_p	position angle of a particle area projected on the disc with respect to the travel direction, deg
r_t	outer radius of a particle area projected on the disc from a feed gate, m	ϕ_u	particle angular distance from the drop point to the edge of the disc, rad
q	diameter correction factor	ϕ_w	angle of a particle area projected on the disc, deg
t_r	moving time of the particle from drop point to the disc edge, s	ω	angular velocity of a disc, rad/s
v_o	particle velocity at the edge of the disc, m/s	ω_t	angular velocity of a disc, min ⁻¹
v_r	radial particle velocity at the edge of the disc, m/s	w_i	mass of particles in each column of the transverse pattern

overlapped pattern was developed by Grift (2000) and Grift *et al.* (2000).

Two commercially available spreaders inspired the feed gates arrangements. The first arrangement was based on a Vicon Rotaflow design. This type of spreader has dual discs and segmented orifice gates, which control the flow rate. In addition, the feeding chambers (including feed gates) can be manually rotated around the disc centres to calibrate the spreader for optimal uniformity. This arrangement lends itself well to the proposed automatic control.

The second arrangement was based on the Lowery 300, a low-cost single disc spreader with dual conical feed gates. This spreader has usually worse spreading performance in uniformity than a dual disc spreader, since producing a symmetric and uniform pattern with a single disc design is complicated for constant flow rates and variable rates. The premise was that a successful uniformity control of the Lowery spreader would imply a much better control of the Rotaflow design. Although the feed gates in the Lowery 300 spreader have a fixed position, in simulation, they were assumed to be

movable, in a circular manner around the disc centre, similar to the Rotaflow design.

The first step in the research was to investigate how the spread pattern changes as a function of the flow rate in the dual disc (Rotaflow) case and the single disc (Lowery) case, using simulation. The next step was to investigate whether rotating the feed gates around the disc centres is sufficient to produce high-quality patterns from both spreader geometries. The quality of a spread pattern was initially evaluated using a global ‘robustness’ criterion based on the (simulated) overlapped field pattern (Grift, 2000). The research revealed that this global criterion was not sufficient to find the optimal pattern, and hence, a second local criterion was added also based on the overlapped pattern. Consequently, it was found that these two criteria do not prevent asymmetric patterns and a third criterion based on a non-overlapped pattern was added. By combining the three criteria, it was possible to find the optimal pattern as a function of the gate settings. The performance of the feed gate control method was assessed using simulation as well as data collected from the Lowery 300 spreader.

2. Literature review

2.1. Model

Patterson and Reece (1962) investigated the motion of particles on a flat spinner disc with straight vanes while neglecting particle bounce and assuming a near-centre feed. They developed models to describe particle motion on the spinner disc and found reasonable agreements between the model predictions and experimental results. They reported that the particle's radial velocity depends on the shape and the friction coefficient between a particle and a disc/vane. Inns and Reece (1962) developed a similar model, assuming off-centre feeding and incorporating particle bouncing against the vanes. They reported that predicting the path of fertiliser particles is difficult due to the particle's irregular shape. Cunningham (1963) developed models for various pitched and curved vanes and conical discs. Cunningham and Chao (1967) derived the generalised trajectory equations on the disc for curved vanes. Brinsfield and Hummel (1975) described the model for a disc with tubes rather than vanes. This type of disc has the advantage of reducing the random motion compared to a conventional vane-type disc. Dintwa *et al.* (2004b) described a generalised simulation model of a particle on a spinning disc fertiliser spreader with pitched straight vanes and a conical disc based on the previous researches.

Mennel and Reece (1963) developed an approximate model for the trajectory of a particle through the air. Pitt *et al.* (1982) derived the approximate particle motion equations in the air to show the distance a particle travels after leaving the disc. In this research, the horizontal particle travel distance by the approximate solutions showed maximum 7% lower than that by the model of Mennel and Reece (1963).

Griffis *et al.* (1983) incorporated on- and off-spinner particle motion developed by earlier researchers into a comprehensive simulation model, compared predicted spread patterns with experiments and found significant differences due to the irregular shape of particles. Olieslagers *et al.* (1996) also generalised the models developed by earlier researchers and found large discrepancies between predicted spread pattern and an experimental distribution owing to ignoring particle interactions. For this reason they suggested a corrected method by adjusting the simulation input parameters to fit the experimental data. In addition, they reported that the angular velocity of the disc, the position of the orifice, shape of the orifice opening, and the mass flow have a major influence on the shape and the width of the spread pattern. Aphale *et al.* (2003) investigated particle trajectories on and off a spinner spreader, comparing

predictions from these models to experimental data for 16 granular fertilisers. The average relative error between the experimental data and the models for the horizontal traveled distance was 20% and 13% for 540 and 810 min^{-1} rotational disc speeds, respectively. Analysis of the model showed that indeed, larger disc speeds would imply reduced sensitivity to variations in the particle speed leaving the disc. Dintwa *et al.* (2004a) suggested calibration of the simulation input parameters using a 'landing area', which represents the collective effect of the various particle interactions during movement along the vane and disc, rather than the orifice area. They assumed that the discrepancies between simulation and measured spread patterns were mostly owing to particle interactions. The researchers identified the most important parameters that affected the 'landing area' such as the mass flow rate, the disc radius, the disc rotational speed, the orifice radial dimensions and the vane pitch, and presented calibration curves for the individual parameters. They suggested that the model, which considers particle interaction, improves simulation results and requires fewer calibrations.

2.2. The effect of fertiliser characteristics

The performance of a spreader and the quality of spread pattern depends largely on the physical properties of the fertiliser (Hofstee & Huisman, 1990). The researchers discussed five important properties, which affect particle motion such as particle size, coefficient of friction, coefficient of restitution, aerodynamic resistance, and particle strength. They reported that particle size has a large effect on particle motion, especially in the air, and the particles with diameter less than 1.0 mm should be removed before spreading, since they cause a higher coefficient of variation and smaller spread width. The influence of the coefficient of restitution was considered important but debatable when a mass flow regime is assumed, rather than individual particles. The particle strength has an indirect effect on the particle motion, since particles with insufficient strength may break during motion; so 15 N was suggested as the minimum breaking force.

Hofstee (1992) investigated the measuring methods for coefficient of friction, coefficient of restitution, aerodynamic resistance coefficient, and the breaking force of fertilisers. He found that the surface material significantly influences the friction coefficients, for instance, the friction coefficient of particles in contact with stainless steel and aluminium surfaces was about 30% higher than those in contact with the surfaces of polyvinyl chloride (PVC) and nylon.

The measured friction coefficient was found to decrease during tests at higher particle velocities: An

increasing velocity from about 1 to about 21 m/s showed a decrease in friction coefficient of about 10–20% and the friction coefficient was found to be independent of the normal load. The coefficient of restitution was largely dependent upon the impact surface: The coefficient of restitution of particles bouncing on stainless steel, aluminium, and PVC showed 50% lower than of those in contact with a nylon surface. Aerodynamic resistance experiments showed that fertilisers with a relatively smooth surface texture had a lower aerodynamic friction coefficient than fertilisers with a rougher surface texture. In breaking force experiments, the larger particle sizes resulted in a larger breaking force, and all fertilisers, except urea prills, had a higher breaking force than the minimum recommended force of 15 N.

Hofstee (1995) discussed physical properties such as coefficient of friction as a function of vane type, pitch angle, and surface of the disc and vane. He reported that experiments did not show the effect of the friction coefficient on the particle motion as predicted by simulation. This is mainly because the model does not assume a mass flow but individual particles, which significantly affects the particle motions on the disc.

Grift *et al.* (1997) validated the model for aerodynamic behaviour of spherical particles in still air as developed in previous research (Mennel & Reece, 1963). They performed fall tests in a 15.4-m tall tower to experimentally determine the aerodynamic properties of fertiliser particles. They characterised the aerodynamic resistance by equalising the fall times of fertiliser particles with perfectly spherical particles. The ratio between the radius of the fertiliser particle and the corresponding spherical particle with an equal fall time was termed the q factor. The values of the q factor ranged from 0.87 for calcium ammonium nitrate (CAN27N), 0.75 for nitrate phosphorous potassium (NPK 12-10-18) and 0.62 for potassium (Potassium60). Walker *et al.* (1997) acquired images of fertiliser particles and correlated the deviation from a sphere (expressed in a 'shape factor') with fall times in order to explain the influence of surface roughness on aerodynamic behaviour.

2.3. The effect of spreading conditions

Parish (1991a) conducted a laboratory test to show the effect of rough landing surfaces on a spread pattern. He showed that a rough surface track made of steel rods had a significant effect on the spread pattern for a turf spreader causing skewness. This result can be explained since the spreader was moved over a rough surface causing erratic particle bounce on the disc. He also

reported that larger and spherical particles were less affected than smaller, irregular particles. Parish (1999a) investigated how spreader fill level affects delivery rate. For a high rate setting, the application rate at 10% hopper capacity showed 7% lower than the application rate at 50% hopper capacity. For the low rate setting, the results showed that the application rate at 10% hopper capacity was 45% lower than the rate at 50% hopper capacity. He concluded that a 40–50% hopper fill level during application, as recommended by ASAE Standard S341.3 (ASAE, 2004), is acceptable. Parish (2002) reported that the fertiliser flow rate has a significant effect on the distribution pattern, especially at low rate settings, and that there were gradual shifts at high rate settings.

Yildirim and Kara (2003) investigated the effect of vane height on distribution pattern with different flow rates. They used a tractor-propelled spreader with a 500 mm flat disc and two materials, triple super phosphate (TSP) and calcium ammonium nitrate (CAN). They reported that the most uniform distribution was obtained with a vane height of 35 mm and orifice diameter of 35 mm for both fertilisers in their particular spreader experiments.

2.4. Spread distribution pattern test

Parish (1986) evaluated spread patterns using 12 different collection methods, using different size pans, and intervals among pans. According to his report, there were significant differences in the rate, swath width, skewness, and coefficient of variation among overlapped patterns. The traditional collection pan method (as standardised by ASAE S341.3) yielded a CV of 8–22%, whereas the floor collection method, which does not have pans but dividers in the floor, yielded a CV of 21–41% and long narrow pans yielded a CV of 27–57%. He stated that the differences might originate from the different amounts of material bouncing into or out of the collection devices. This investigation was extended by Parish *et al.* (1987) which showed the actual pattern differences in the field.

Parish (1991b) studied the effect of fertiliser bouncing into and out of collection pans on spread patterns. The experiments showed that the fertiliser amounts owing to bouncing out of the pans and bouncing from the floor into the pans was significant. However, bouncing had little effect on the spread pattern uniformity and skewness.

Tissot *et al.* (1999) investigated the transversal distribution patterns of blended fertilisers. The results for a two-component blend showed different throw distances owing to varying particle properties between

the blends, influencing not only aerodynamic behaviour but particle motion on the disc as well.

2.5. *Alternative methods for measuring distribution patterns*

Several researchers have investigated and developed alternative methods to predict a spread pattern compared to the traditional method (ASAE, 2004), which uses collection trays that are lined up perpendicularly to the line of travel of the vehicle or aircraft. After the spreading run, the mass collected in each tray is weighed and a simulated overlapped pattern is generated using software such as developed by Grift (2000). The collection tray procedure requires high investments in countries with adverse weather conditions requiring indoor facilities. An alternative approach was proposed by Hofstee (1994), who discussed an ultrasonic transducer arrangement to measure the velocity and direction of particles leaving a spinner spreader. The particle velocity was measured using the Doppler frequency shift of the received acoustic signals. The measured particle diameters showed a large deviation from true diameters owing to a non-linear frequency response of the ultrasonic sensors, as well as the highly sensitive acoustic backscatter properties of small particles.

Grift and Hofstee (1997b) developed an optical device to measure the radial velocity and diameter of individual fertiliser particles. Two sensor arrays composed of 30 photo-sensitive sensors ('OptoSchmitts') each, which are connected in a single logical AND function, were monitored when the particle blocks the light source. The particle velocity was calculated from the time difference corresponding to the particle moving from the upper array to the lower, and the diameter was derived using the time interval during which the particle blocks each sensor array. The test results showed the accuracy of the measured diameter of an air gun pellet was within 2% in one-dimensional measurement and in two-dimensional measurements, the accuracies of the measured diameters and velocities were between 2% and 5%, respectively. To test the optical device, Grift and Hofstee (1997a) developed a fertiliser particle accelerator, capable of discharging fertiliser particles with a fixed direction and a maximum discharge velocity of 52 m/s. The variation in measured discharge velocities was reported about 5–10% of the mean discharge velocity.

Grift and Hofstee (2002) extended their research to an alternative method of fertiliser spread pattern determination. Here the landing locations of fertiliser particles were predicted using a ballistic model that takes the

measured velocities and diameters as inputs, eliminating the need for collection pans. The optical sensor was mounted on the hopper of a single spinner fertiliser spreader and rotated along the vertical axis of the spreader to scan the spreading zone. In the centre of the spreader underneath the disc, an absolute angle encoder was fitted to measure the angle of the sensor. They reported that the sensor was reliable and robust enough for field application.

To measure the tangential and cylindrical spreading distribution, Reumers *et al.* (2003a) used a compact collection tray arrangement, composed of a 36 compartments, each 10° wide and arranged circularly at 1 m from the centre of the disc. They quantified the influence of vane length, mass flow rate, particle size and fertiliser type on both the tangential and the cylindrical distribution patterns. In agreement with Hofstee (1995), they confirmed that particle mass flows with a larger mean diameter achieved higher velocities on the disc. Furthermore, a smaller average particle size led to a higher mass discharge flow rate from the hopper, and a higher mass flow rate shifted the cylindrical distribution to a lower vertical position.

Reumers *et al.* (2003b) extended their research to acquire the positions and velocity vectors of the particles discharged from the disc by imaging. They found that the simulated distribution was smaller than the measured distributions in the radial direction, and found a shift and a wider spread in the tangential direction.

Cointault *et al.* (2003) developed an imaging system to evaluate the fertiliser distribution on the ground by measuring the velocity and direction of particles after their discharge from the disc. The velocity and direction of particles were used as initial conditions in ballistic models to predict the landing positions of the particles. To develop an inexpensive but high-performance system they combined a high-resolution, low-speed camera with strobe lighting. They, however, stated the system costs were too high for mass production, and that the imaging system alone was more expensive than a commercial spreader (12,000 Euros).

Hensel (2003) suggested using a digital imaging system to distinguish the fertilisers on the ground from soil components by their specific differences in colour, shape and size. The image processing system was mounted on an all-terrain vehicle with a global positioning system (GPS). They reported that the particle detection rate was affected by the fertiliser nature and environmental factors such as light, soil condition and vegetation. In the clod-free soil without biomass, the detection rate was reported to be close to 100%, but mulch and vegetation decreased the accuracy.

2.6. Variable rate application

Fiala and Oberti (1999) investigated the performance of a commercial automatic rate control system for a centrifugal spreader. The control system of a dual disc spreader consisted of a travel speed sensor, electric motors, proximity sensors, and an on-board computer. The test results showed a linear relationship between the fertiliser flow rate and the travel speed of the tractor. They also stated that the fertiliser flow rate was affected significantly by the hopper fill level.

Fulton *et al.* (2001) assessed the performance of variable rate spinner spreaders. The experiments showed desirable, Gaussian-shaped patterns, for an application rate of 56 kg/ha, however, the pattern changed to an undesirable 'W' shape at the higher application rate of 168.1 kg/ha. They suggested using other devices such as adjustable fins on the spinner or rear divider to improve pattern shifts at different rates for accurate application.

From the above literature review, it can be seen that earlier research focused on the analysis of particle dynamics and physical properties for the design of spreaders. Recently, research has been performed to test automatic control systems for site-specific fertiliser application. Today, many manufacturers offer variable rate control systems to apply precise amount of fertilisers, but the uniformity of the spread patterns is not guaranteed. To date there is no system on the market that truly controls the uniformity of the spread pattern using a feedback control system. This research aims to develop such a system.

3. Materials and methods

3.1. Simulation model

Olieslagers *et al.* (1997) reported that a varying flow rate has a significant effect on the spread width and shape of the transverse distribution pattern, and that 'M' and 'W' shapes cause high coefficients of variation. In this research to show how spreader patterns affect on various application rates for the dual disc spreader with segment-type feed gates, as well as the single-disc spreader with conical feed gates, spreader simulations were carried out with varying flow rates using a simulation model.

3.1.1. Particle motion on the disc

Patterson and Reece (1962) derived equations governing the particle motion while sliding along a flat disc equipped with radial straight vanes. The equations are based on a force equilibrium among the centrifugal force, the gravity force, the Coriolis force and friction

force as follows:

$$m\ddot{r} + 2\mu_v m\dot{r}\omega - m\omega^2 r = -\mu_d mg \quad (1)$$

where: r is the radial position of the particle on the disc in m; \dot{r} and \ddot{r} are the first and second derivative of r with respect to time, respectively; m is the particle mass in kg; ω is the angular velocity of the spinner disc in rad/s; μ_v is the particle/vane friction coefficient; μ_d is particle/disc friction coefficient; and g is the gravitational acceleration in m/s^2 . The particle angular distance from the drop point to the edge of the disc ϕ_u in degrees can be calculated from Eqn (2):

$$\phi_u = \omega t_r, \quad (2)$$

where, t_r is the moving time in s of the particle from drop point to the edge of the disc.

The particle exit angle β_o in degrees can be computed by Eqn (3):

$$\tan \beta_o = \frac{v_t}{v_r} = \frac{\omega r}{\dot{r}} \quad (3)$$

where v_t is the tangential velocity in m/s and v_r is the radial velocity in m/s at the edge of the disc.

The total outlet velocity of the particle v_o in m/s can be calculated as

$$v_o = \sqrt{\dot{r}^2 + (\omega r)^2} \quad (4)$$

3.1.2. Particle motion through air

The equations of particle motion in the air to predict the landing position of the fertiliser particles are (Mennel & Reece, 1963):

$$\ddot{x} = -K\dot{x}\sqrt{\dot{x}^2 + \dot{y}^2} \quad (5)$$

$$\ddot{y} = -K\dot{y}\sqrt{\dot{x}^2 + \dot{y}^2} - g \quad (6)$$

where x is the horizontal distance of the particle between the end of the vane and the location during the ballistic flight, y is the vertical distance of the particle between the disc and the location during the ballistic flight and g is the gravitational acceleration. There are two measured inputs, velocity and particle radius, and three parameters: (1) initial launch height (measured before testing); (2) density of air; and (3) true density of the fertiliser particle. The aerodynamic resistance coefficient K was redefined by Hofstee (1992) as taking the q factor, a material-specific constant, into account as follows

$$K = \frac{3}{8} C_D \rho_{AIR} \frac{1}{\rho_p q r_p} \quad (7)$$

where: C_D is the drag coefficient of the sphere; ρ_{AIR} is the density of air in kg/m^3 ; ρ_p is the density of the

particle in kg/m^3 ; r_p is the radius of the particle in m; and q is the diameter correction factor ($0 < q < 1$).

The factor K was assumed constant for a particular particle, since the drag coefficient is virtually constant ($C_D = 0.4$) for high Reynolds numbers (high velocities), especially for non-spherical particles that introduce a turbulent flow regime at lower Reynolds values.

The ballistic model, as presented here, is only valid for a sphere. Since a fertiliser particle, due to its shape and texture, would have a longer flight time than a perfectly smooth sphere, it was treated as a smaller sphere (which would also have a longer flight time) by multiplying the diameter by a correction factor q ($0 < q < 1$). This factor was retrieved from fall tests performed in earlier research reported by Grift *et al.* (1997).

3.2. Simulation of distribution pattern

3.2.1. Dual disc spreader with segment-type orifice gates

Previous research by Olieslagers *et al.* (1996) was reviewed to investigate a spread pattern for the spinner spreader with dual discs and segment orifices similar to the Vicon Rotaflow principle.

Figure 1 shows the dimensions of a segment orifice described by r_b and r_e , the inner and outer radii of the segment, ϕ_d is the segment angle which controls the flow rate of fertilisers, and ϕ_o is the position of the orifice with respect to the travel direction. In this research, values were set for r_b of 0.05 m and r_e of 0.1 m.

In the simulation of the spread pattern, the spreader was assumed to be stationary, and the dual discs were considered to be mirror images. For simplicity reasons, a flat disc and four straight vanes were assumed in this simulation. In the simulation, the particles were introduced onto the disc according to a lattice in the gate area, which had an angular spacing of 2.5° and a linear spacing of 5 mm. Each lattice node represented 108 particles with diameters drawn from the particle distribution, which had a mean diameter of 2.52 mm and a standard deviation of 0.65 mm, equal to the diameter distribution of Urea used in validation. The spreader and particle characteristics used in this simulation were: vertical distance from ground to disc $h = 0.9$ m; $\omega_t = 1000 \text{ min}^{-1}$; disc radius $r_d = 0.4$ m; $\phi_o = -20^\circ$; $\rho_{AIR} = 1.2 \text{ kg/m}^3$; $\rho_p = 1100 \text{ kg/m}^3$; $C_D = 0.4$; $q = 0.87$; $\mu_v = 0.2$; and $\mu_d = 0.2$.

Figure 2 shows the simulation results of transverse distribution patterns for different fertiliser application rates by changing the segment angle ϕ_d . Olieslagers *et al.* (1996) reported a positive relationship between the fertiliser application rate and the segment angle and no particle flow for a small segment angle. In this simulation, therefore, a minimum segment angle of 15°

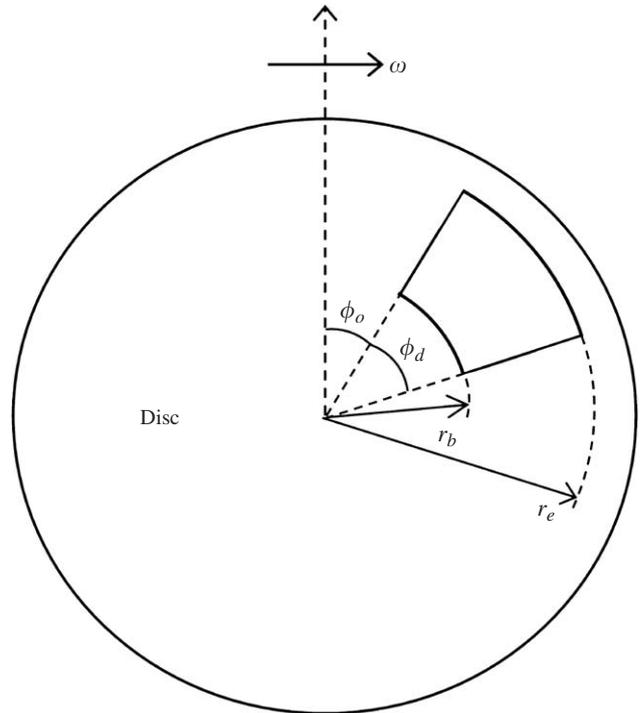


Fig. 1. Dimensions of segment orifice; ϕ_d , segment angle of the orifice; ϕ_o , position angle of the orifice; r_b , inner radius of the segment orifice; r_e , outer radius of the segment orifice; ω , angular velocity of a disc

was used and all model parameters of the spreader were adjusted to generate a desirable Gaussian shape at this segment angle (Grift, 2000).

From Fig. 2, it is clear that the spread width increases with increasing fertiliser application rates, and that the Gaussian shape morphs into an 'M' shape, similar to findings by Olieslagers (1997) and Fulton *et al.* (2001).

3.2.2. Single disc spreader with conical-type feed gates

Figure 3 shows a spinner-type spreader with conical feed gates by which the particle areas on the disc are deposited similar to the Lowery 300 spreader. The gate opening width is the distance between inner and outer radii, r_i and r_t , of the particle drop area projected on the disc. ϕ_b represents the angle between two gate centres, ϕ_p represents gate 1 position, the angle between the gate 1 centre and the travel direction, and ϕ_w is the angle of gate width, which was fixed at 18° in this research. Since this angle is fixed, the mass flow rate of this type of spreader is changed by varying the vertical gate position.

Figure 4 shows the simulation results of distribution patterns for different fertiliser application rates by changing the gate opening width. In this simulation, the minimum gate opening width of 0.02 m was used and, as in the previous case, all parameters of the

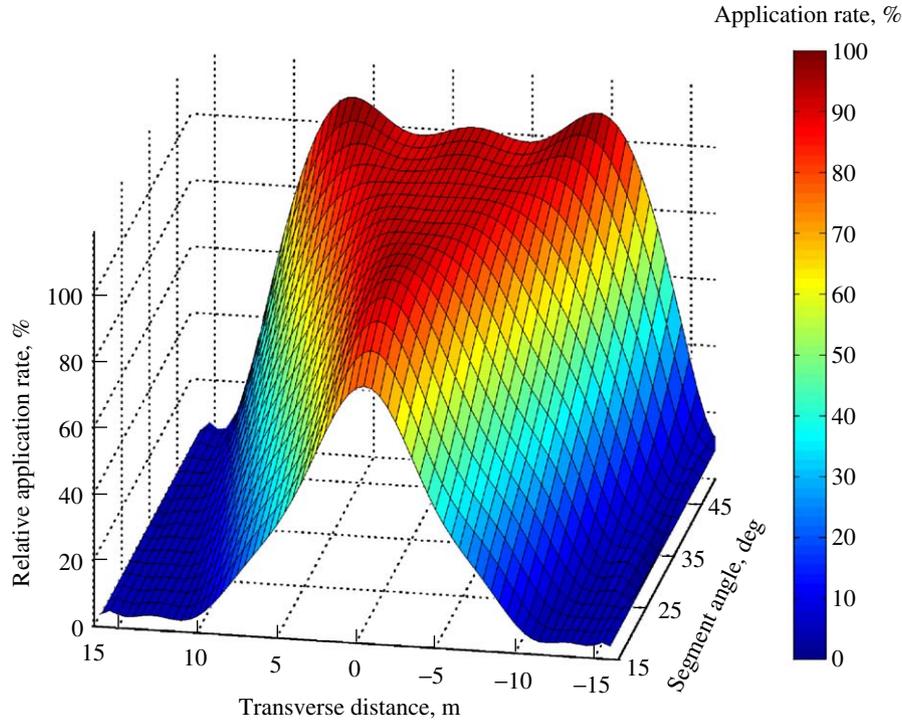


Fig. 2. Transverse distribution various patterns for various segment angles in dual disc case

spreader were adjusted to obtain a Gaussian shape at this gate opening width. As in the dual disc case, the particles were introduced onto the disc according to a lattice in the gate area, which had an angular spacing of 2.5° and a linear spacing of 5 mm, with 108 particles per lattice point, using the same diameter distribution. The spreader and particles characteristics used in this simulation were: $h = 0.35$; $\omega_t = 540 \text{ min}^{-1}$; $r_d = 0.41 \text{ m}$; $r_i = 0.05 \text{ m}$; $\phi_b = 21^\circ$; $\phi_p = 14^\circ$; $\rho_{AIR} = 1.2 \text{ kg/m}^3$; $\rho_p = 1100 \text{ kg/m}^3$; $q = 0.87$; $\mu_v = 0.3$; and $\mu_d = 0.3$.

As is clear from Fig. 4, as the fertiliser application rate increases, the spread pattern becomes skewed to the positive direction in the transverse distance axis.

The previous simulations indicate that maintaining a high uniformity under varying application rates with the spreader geometries as studied, is impossible without a feedback control method.

3.3. Spread pattern optimisation using adaptive feed gate control

3.3.1. Feed gate adaptation algorithm

The objective of ground-based fertiliser application is to spread material at a preset rate and an acceptable uniformity, while minimising the total travel distance and operation time. As shown in the previous simulations for a dual and single disc spreader, maintaining a

high uniformity under changing application rates is not possible without adaptive intervention.

The quality of a spread pattern is traditionally expressed by the average application rate (the mean of multiple overlapped patterns) at a chosen swath width and the uniformity expressed in the statistical CV. Based on a rule of thumb, a CV lower than 15% is assumed to prevent damage to the crop at a pre-determined swath width.

Olieslagers *et al.* (1997) reported that in order to make an efficient overlap, the shape of the distribution pattern and the spreading width should remain constant for a variable flow rate. They also reported that the pattern has to be symmetrical, since non-symmetric patterns cause non-uniformity, particular during a back and forth operation, in which spreading overlap is made by adjacent passes in the opposite direction of travel. Grift (2000) reported a Gaussian-shaped pattern was the most desirable pattern, triangle and trapezoid patterns were desirable, but 'M', 'W', and skewed patterns were not desirable and should be avoided. He also defined a spread pattern quality indicator termed 'robustness', a global measure that takes a range of swath widths into account. A robust pattern is inherently forgiving, meaning that variations in swath width, either deliberate or owing to driving path errors, will not have great effects on the uniformity. According to his research, the robustness is the average CV from a swath width of zero

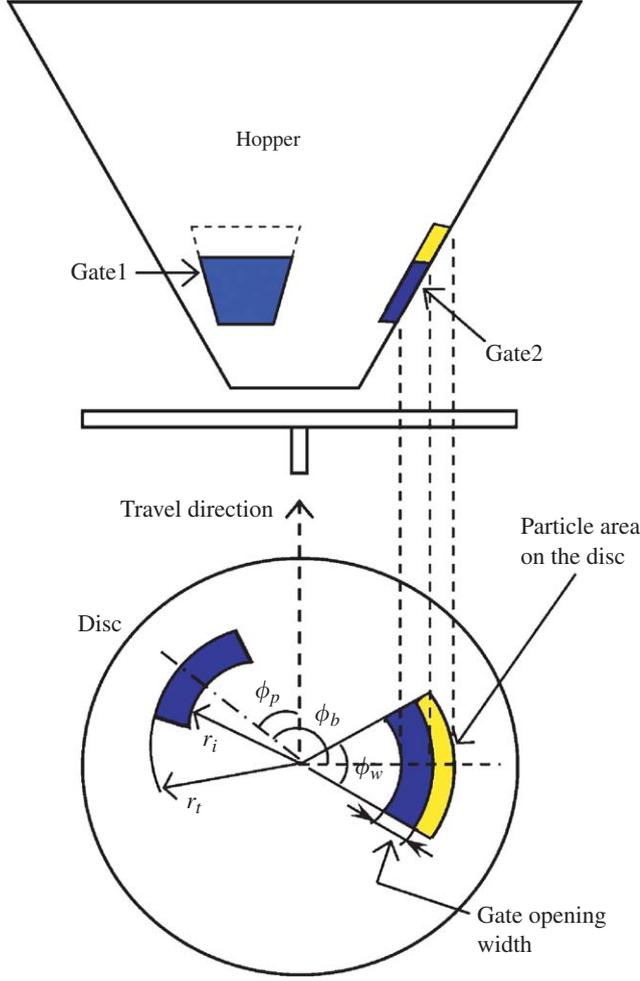


Fig. 3. A spinner type spreader with conical feed gates; r_i , inner radius of particle area projected on the disc from a feed gate; r_o , outer radius of particle area projected on the disc from a feed gate; ϕ_b , angle between feed gates; ϕ_p , gate 1 position, angle between gate centre and the travel direction; ϕ_w , angle of gate width

meters to the maximum swath width where the pattern still exhibits an acceptable uniformity (such as 15%) and desirable patterns have a lower robustness value than undesirable patterns.

In this research the robustness can be redefined as the average CV from zero to a desired swath width. For uniformity control, robustness can be chosen as the first criterion to acquire desirable patterns since undesirable patterns such as ‘M’, ‘W’, and skewed patterns will be filtered out.

In previous research (Olieslagers *et al.*, 1996; Yildirim & Kara, 2003) it was found that the initial drop location of particles on the disc was one of the most sensitive factors affecting the spread pattern. This inherent sensitivity allows for optimisation of the pattern for varying application rates by controlling the position of

the feed gates. Simulations were carried out according to the ‘robustness’ criterion with the different gate positions for a dual disc spreader with segmented gates. For this simulation, the segment angle ϕ_d was set to 50° , implying a constant flow rate, and the position of segment orifice ϕ_o was simulated from 0° to -100° for one disc and the pattern from the other disc was considered a mirror image. The resulting simulated patterns were consequently overlapped at a swath width of 10 m, and the robustness value was computed for every possible gate position. This robustness factors will be unified with other criteria for choosing the optimal gate position. Back and forth mode was used since it represents the worst-case scenario and is most popular (Parish, 1999b).

Although the robustness criterion can be used to filter out undesirable patterns such as ‘M’ shapes and ‘W’ shapes, it is a global measure, which takes many potential swath widths into account. To find an optimal spread pattern at a chosen swath width, a local criterion was added which takes the average CV in an arbitrary range of 90–110% of this ‘work point’ into account.

After filtering patterns with the (1) Robustness and (2) ‘work point sensitivity’ criteria, still patterns were found that were off-centre of the driving path, which can cause major non-uniformity.

Therefore, as a third criterion, the weighted arithmetic mean d_w , which is a function of the non-overlapped single transverse pattern, was added to avoid an offset pattern as follows:

$$d_w = \left| \frac{\sum_{i=1}^n w_i d_i}{\sum_{i=1}^n w_i} \right| \quad (8)$$

where: n is the number of column vectors in the transverse pattern; d_i is the distance of each column from the travel direction (tramline) in the transverse pattern; and w_i is corresponding weight of each column in the transverse pattern.

The weighted arithmetic means were calculated from each non-overlapped single transverse pattern by the different gate positions. For this simulation, n (can be considered as the number of pans in traditional pan collect methods) was 33, and for d_i the left side from the centre of the driving path was considered as negative direction.

The single patterns with larger offset have a higher value in the factors of weighted arithmetic means, and can be filtered out.

Figure 5 shows the summation of all criteria with the different gate positions. The minima found in the summation plot represent the optimal spread pattern according to the ‘robustness’, ‘work point sensitivity’ and weighted arithmetic mean criteria. The minimum

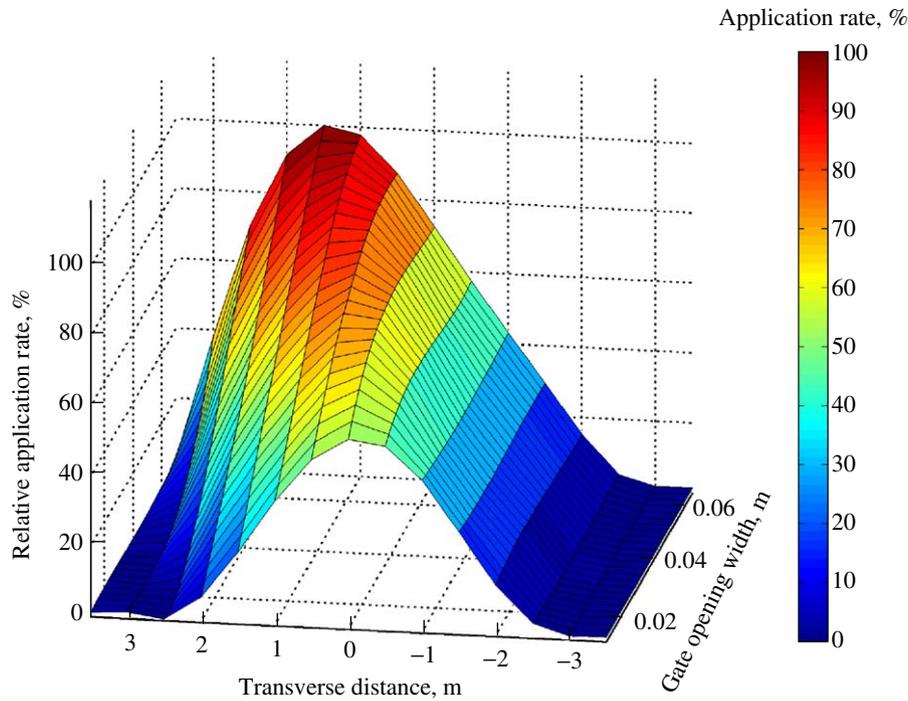


Fig. 4. Transverse distribution patterns for various gate opening widths in single disc case

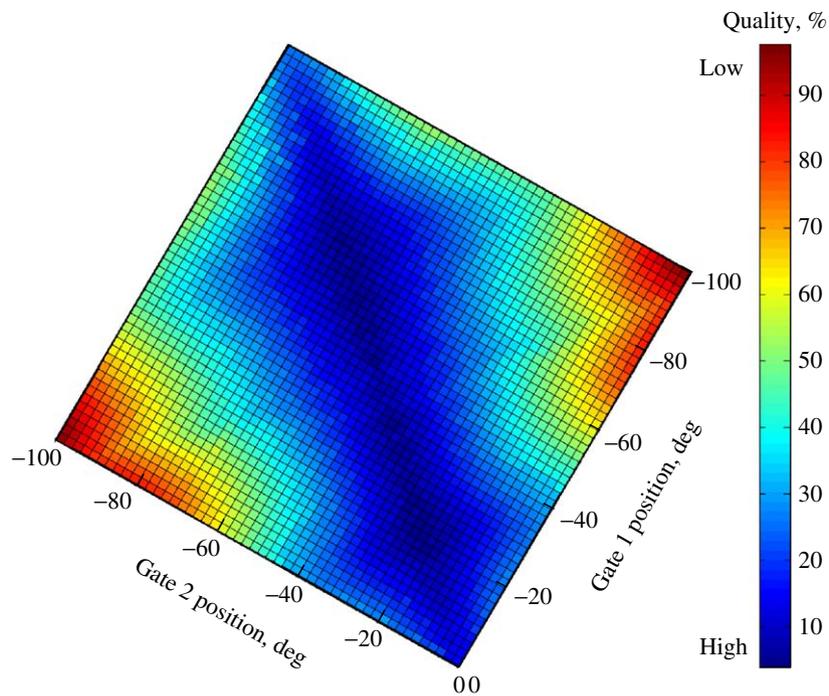


Fig. 5. Union of all normalised criteria with the various gate positions in dual disc case

CV was found at -60° for the both position angle of the orifice gates 1 and 2.

Figure 6 shows the three-dimensional distribution pattern in the field by the corresponding positions of the segment orifices.

3.3.2. Simulated feed gate adaptation, dual disc, segment orifice gate case

Figure 2 showed that for increasing application rates, the spread width of a dual disc spreader with segment orifice gates increased and the pattern became 'M'

shaped. To find a better spread pattern shape for high application rates, the gate adaptation algorithm as discussed in the previous section was developed where patterns were selected that satisfied three quality criteria. Ideally, to ensure a highly uniform pattern, the basic shape and spread width of the pattern should remain constant under varying application rates. Therefore, the optimal spread width was set to 10 m, half of 20 m of the transverse width at the minimum rate of the segment angle of 15° in Fig. 2.

Figure 7 shows the simulated transverse distribution patterns after application of the feed gate adaptation algorithm for the dual disc case. Compared to Fig. 2, note that the transverse spread patterns are approximately of equal width, symmetric, and near-Gaussian. This simulation shows that a simple adaptation algorithm based on three criteria, is capable of producing excellent patterns for variable rate applications.

3.3.3. Simulated feed gate adaptation, single disc, conical feed gate case

In the previous section, simulations showed that the problem of emerging M-shapes for higher application rates for a dual disc spreader could be solved by adaptive gate control. For a single disc case with a conical gate, the problem was severe skewness for higher application rates (Fig. 4).

To find optimal spread pattern shapes for varying rates in a single disc case, the gate adaptation algorithm was applied once more. The swath width was chosen as 2.5 m, similar to the working width of the Lowery 300 spreader.

Figure 8 shows the transverse distribution patterns for varying rates, after application of the feed gate adaptation algorithm for the single disc spreader. Compared to Fig. 4, the distribution pattern widths are slightly wider and the pattern shapes are still slightly skewed to the left, as the application rate increases. However, the optimised pattern shape shows far superior performance than Fig. 4 without gate adaptation, showing that gate adaptation works even in the worst-case scenario. Comparing the results from the dual disc spreader (Fig. 7) to the single disc spreader (Fig. 8), the dual disc spreader according to the Rotaflow principle is clearly a better candidate for adaptive pattern optimisation than the single disc spreader (Lowery 300).

4. Implementation of feed gate adaptation algorithm

Previous research as reported by Olieslagers *et al.* (1996) and Dintwa *et al.* (2004a) showed unacceptable discrepancies in simulated distribution patterns of a spinner spreader compared to measured patterns. In this research, instead of predicting particle-landing locations

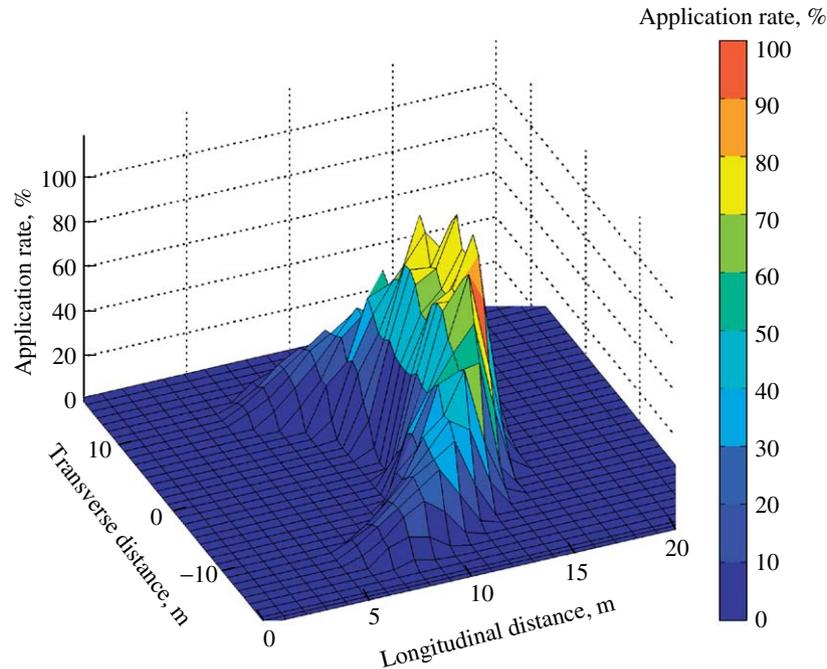


Fig. 6. Three-dimensional distribution pattern after feed gate adaptation in dual disc case (position angle of the orifice 1 $\phi_{o1} = -60^\circ$; position angle of the orifice 2 $\phi_{o2} = -60^\circ$)

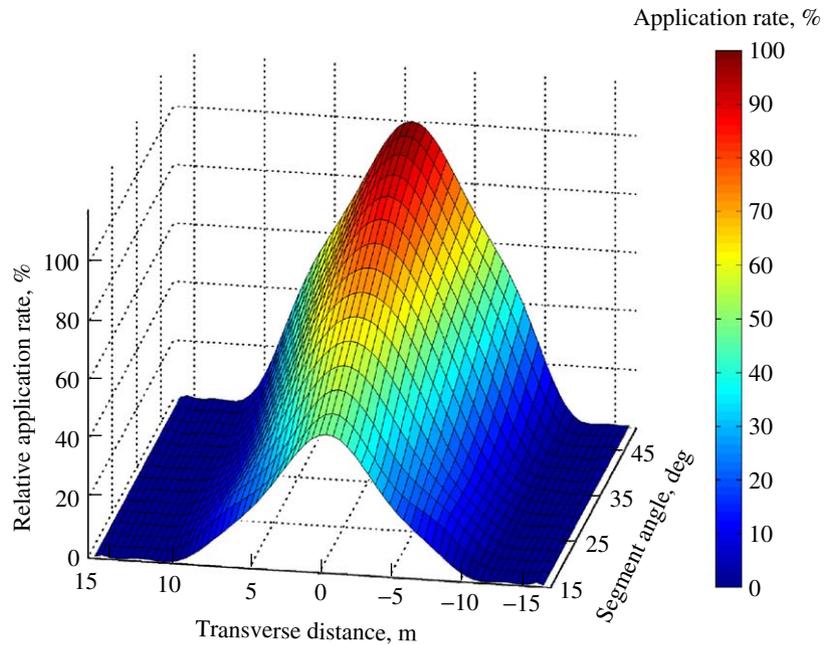


Fig. 7. Dual disc spreader transverse distribution patterns for varying segment angles after feed gate adaptation

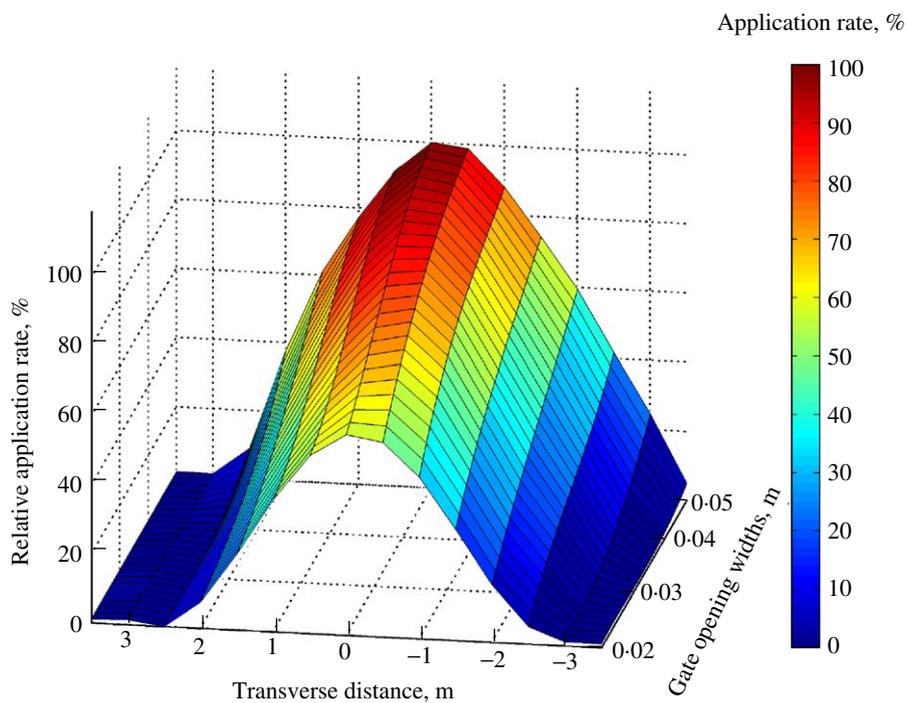


Fig. 8. Single disc transverse distribution patterns for varying gate opening width after feed gate adaptation

using models, an optical sensor was used as a feedback mechanism. Since the dual disc spreader is a better candidate for optimisation, to investigate the scope of the adaptive gate control method, the worst-case scenario, being the single disc spreader, was chosen as a validation tool.

4.1. Spread pattern measurements

To implement the adaptive feed gate algorithm in a real spreader, a Lowery 300 spreader was used as a test bed. Although the Lowery spreader has two 60 mm by 40 mm (width by height) feed gates through which the



Fig. 9. Optical sensor mounted on a Lowery 300 fertiliser spreader

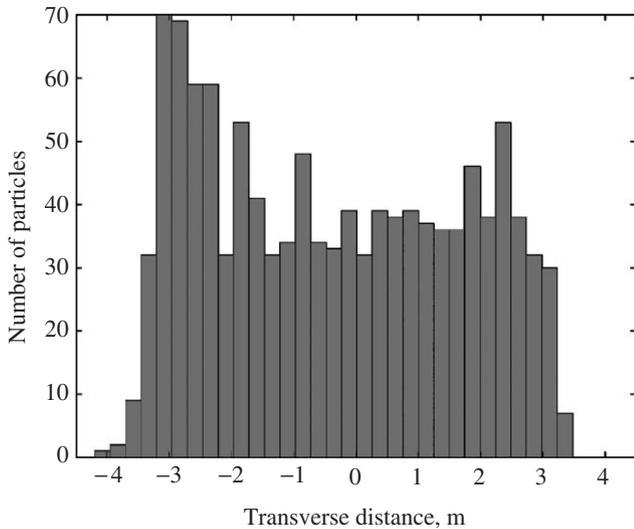


Fig. 10. Transverse pattern in the field for two feed gates opening

fertiliser material is fed onto the disc, the data from a single gate was used in experiments, since the gates cause overlapping particle streaks that cannot be reconstructed by the gate when both are used simultaneously.

Therefore, experiments were carried out with a single open gate and the data from the other gate was assumed identical.

Originally, the spreader had a conical disc with 5° conical angle and four pitched vanes, however, for this research a flat disc of 0.42 m diameter and four radial straight vanes was constructed. Before the test, the speed of the power take off (PTO) shaft was set to 370 min⁻¹, the hopper was filled half full with urea fertiliser and the gate was set to 50% opening.

Figure 9 shows the optical sensor attached to a Lowery 300, single disc fertiliser spreader. The sensor was mounted vertically with a horizontal bar that connects to a bearing in the centre of the disc. It was moved around the spreader rim with two motors and rubber friction wheels. End switches were used to automatically alternate the direction of travel of the motors at the end of the cycle. In the centre of the spreader, underneath the impeller, a 12-bit absolute angle encoder (AG 612 WKRP4096 GRAY, Max Stegmann GmbH, Donaueschingen, Germany) was mounted, which measured the angle of the sensor relative to the center of the disc.

Figure 10 shows the transverse pattern of the predicted fertiliser landing positions from six cycles of the optical sensor, and the pattern is obviously skewed in the negative direction.

Figure 11 shows the CV swath width plot and the application rate and swath width plot. The solid horizontal line indicates 15% CV limit and the dashed vertical line indicates the swath width of 2.5 m. From the

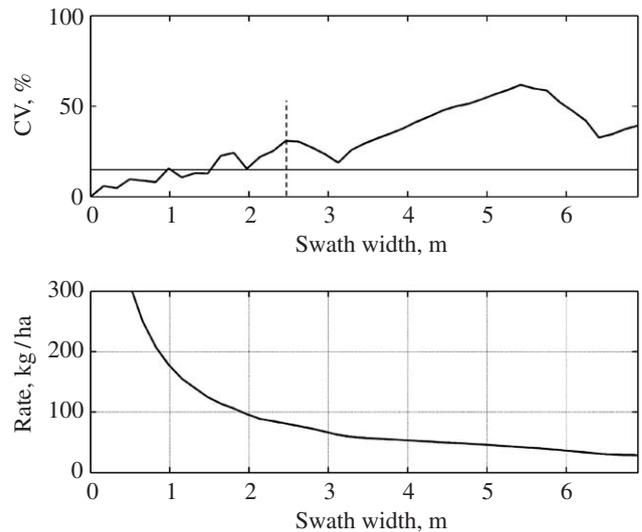


Fig. 11. Coefficient of variation (CV) and rate vs swath width for two feed gates opening in back and forth mode; The solid horizontal line indicates 15% CV limit and the dashed vertical line indicates the swath width of 2.5 m

CV swath width plot it is clear that it is impossible to produce an acceptable pattern without adaptive gate control, as evidenced by the CV being higher than 15% from a swath width of 1 m and up.

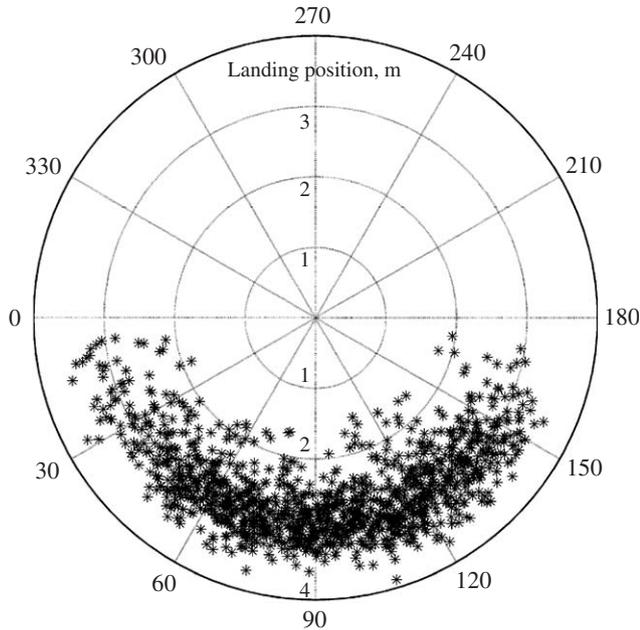


Fig. 12. Predicted fertiliser landing positions by angle for single gate

Figure 12 shows the predicted fertiliser landing positions by angle from the single gate, set to 50% opening. For this experiment data the optical sensor was rotated for six cycles.

4.2. Feed gate adaptation applied to single disc, conical feed gate case

For the optimal positions of feed gates, the feed gate adaptation algorithm with measured data was applied. Figure 13 shows the summation of all three criteria with the different gate positions in back and forth mode. The minimum ϕ_b , the difference in angle between the gates, was set at 18° to avoid physical interference. Therefore, the gate positions with a difference between the gates of lower than 18° had the lowest quality and were ignored. The optimal pattern with a minimum average CV at 2.5 m swath width was generated by rotating gate 1 -10° and gate 2 through -18° , leading to ϕ_b , the difference, being 28° . Figure 14 shows the transversal distribution pattern, which would emerge in the field. Compared to Figure 10, the pattern is superior, albeit not near-Gaussian.

Figure 15 shows the overlapped distribution pattern from the single distribution pattern of Figure 14. In Figure 15 the dotted horizontal line indicates the average applied fertiliser rate and the dashed vertical lines are the driving paths, so swath width was set to 2.5 m.

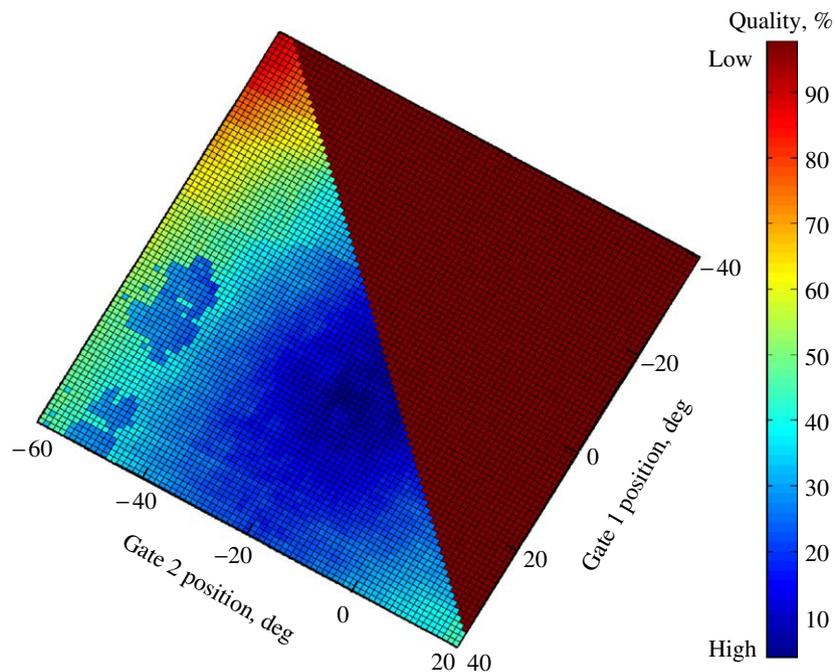


Fig. 13. Union of all criteria with the different gate positions for the measured data

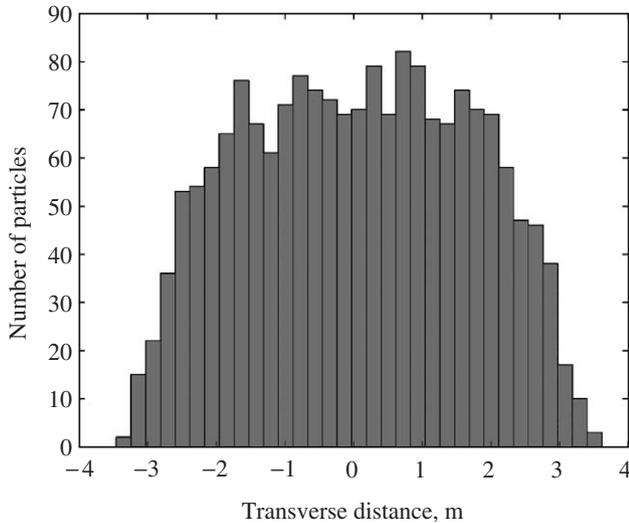


Fig. 14. Transverse distribution pattern in the field for adaptive two feed gates opening (position angle of the gate $\phi_p = 10^\circ$; angle between feed gates $\phi_b = 28^\circ$)

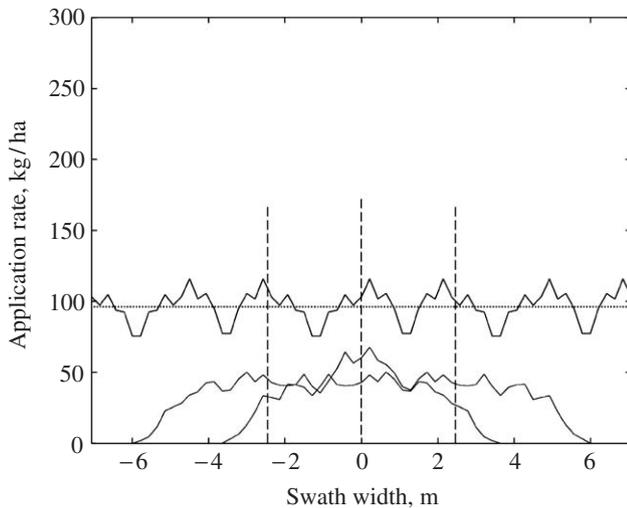


Fig. 15. Overlapped spread pattern for adaptive two feed gates opening in back and forth mode

5. Conclusions

To show the dependency of spread pattern variability on the application rate, simulations using models from the literature were carried out for two cases: (1) a Vicon Rotaflow dual disc design, which has dual segmented feed gates and uniformity control through rotation of the feeding chambers; and (2) a basic single disc spreader design (Lowery 300) with two conical feed gates.

The simulation results for the dual disc (Rotaflow) design showed that for high application rates the pattern

becomes poor ('M'-shaped) even though the pattern for low rates was good. The analysis for the Lowery 300, single disc spreader showed that for high application rates the pattern becomes skewed, again even though the pattern for low rates was good.

A feed gate adaptation method was developed, which uses an optical feedback sensor, developed in earlier research, to optimise the pattern uniformity. Simulations showed that the feed gate adaptation method is capable of producing high-quality patterns for any given application rate, in both cases, the dual disc Rotaflow design spreader with segmented orifice gates, as well as the single disc spreader with conical gates (Lowery 300).

The performance of the adaptive feed gate control method was tested using data collected from the single disc Lowery 300 spreader. Although the original, uncontrolled pattern of this spreader was of low quality, the adaptive feed gate control algorithm was capable of producing an acceptable pattern.

In future research, the adaptive feed gate control method needs to be field tested, using the optical feedback sensor integrated with computing hardware, networking as well as actuation. More tests are needed to show the performance for multiple rate settings. In the current research, the dual disc Rotaflow design was superior to the Lowery 300 for pattern optimisation.

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