Study of the granular fertilizers and the centrifugal spreader using Discrete Element Method (DEM) simulations

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The need for accurate and uniform fertilizer spreading
Mineral fertilizers are used to supply the natural mineral balance needed for good crop yields. For the past few decades, there has been a growing concern about the environment associated with the use of soil fertilizers. Environmental problems such as water pollution, and the decline in biodiversity are known consequences. Finally, both over and under-application lead to yield losses and ecological devaluation. For these reasons, accurate spreading is absolutely necessary to minimize costs and maximize profit.

In Europe, over 90% of the fertilizers are distributed using spinning disc spreaders (Figure 1). The popularity of spinning disc spreaders lies in their relatively low cost and relatively high accuracy. Furthermore, they allow a high working width (more than 36m nowadays) and easy maintenance.

Depending on the scale of the application, a centrifugal spreader contains a large bin of 0.5-8 m³. Since the bulk density of fertilizer is roughly 1000 kg/m³, current technology easily covers a few ha without refilling the bin. Directly under the bin, a spinning disc is mounted, which is driven by the tractor transmission. The particles are, through the bin orifice, dropped on the disc on which they are accelerated and thrown in the field, forming the spread pattern. Usually, 2 discs

1 Assuming 100kg/ha dose
rotating in opposite direction are used to improve the symmetry of the spread pattern. At the same time the working width is doubled.

The shape of the pattern is ideally trapezoidal. By pattern overlap, one prevents large dose variations. A uniform coverage of 100% can be achieved theoretically when driving precisely on adjacent lanes (Figure 2).

![Figure 2: Definition of working width and approximate shape of the spread pattern of a twin disc centrifugal spreader.](image)

The performance of these machines is highly dependent on the particle properties (e.g. friction coefficients, shape) and the quality of the fertilizer. This results in large differences in spread patterns depending on the fertilizer type (Hofstee, 1995) as well as the prevailing weather conditions (e.g. air humidity). With working widths reaching 36 m and more, spread patterns get increasingly less uniform (Olieslagers, 1997). Some manufacturers picked up on this problem by building online controlling systems for the particle flow. In addition, the availability of GPS devices nowadays allows more accurate spreading.

**The need for modeling**

In order to investigate the variability of the spread pattern, performance tests are often done in large spreading halls. In these spreading halls, a collector tray covering the whole working width is positioned behind the disc(s). After the spreading application, the contents of the baskets are measured automatically yielding a mass distribution of the entire spread pattern area. This measurement methodology allows calibration and adjustments of the machine parts. Despite their need, these tests are expensive, time consuming, and require huge amounts of fertilizer. However, to reduce the experimental cost to an absolute minimum, models are required that can

**About the author**

Paul Van Liedekerke (1976) studied industrial sciences in Belgium. In 1999 he obtained his Master diploma in Physics at the University of Ghent, with specialization in radioactivity. He completed a post-graduate study in Environmental Technology, specializing in acoustic pollution. In 2000 he started as scientific collaborator at the KULeuven, at the Lab of Mechatronics, BioSensors and Statistics (MeBioS), where he specialized in numerical modeling of van biologic and granular materials. On September 19th 2007 he obtained his PhD in bio-engineering sciences at the KULeuven, Belgium.
predict the particle flow from the bin to the field. More specifically, there is a need for describing the functioning of a centrifugal spreader by modeling, starting from geometry of the spreader and the fertilizer properties. In addition, modeling will help to understand the complicate relation between the properties of a fertilizer and its spreading pattern for given machine settings.

Introduction to DEM

The Discrete Element Method (DEM) is a numerical technique suitable for computing the motion of particles. The motion of an individual particle is determined by the forces acting on it. In a granular system these forces are typically gravity, and contact forces arising from collisions of the particle with other particles and machine parts. The power of a numerical model not only lies in the reduction of experiments, it is also a powerful tool to optimize processes. Agricultural industry may have a good potential for DEM. In case of the fertilizer industry, beside the losses in spreading applications, fertilizer is also wasted during handling and transport, with rates of been reported for 0.5% to 5% (IFA, 2000). DEM simulations could help to avoid these losses to give solutions or methods to minimize stresses on the fertilizer particles by model parameter optimization.

DEM Algorithm flow

Generally, a DEM algorithm consists of 6 major components (tasks) which are applied to a particle system every time step in following order (Figure 3):

These 6 steps may vary in length, accuracy and efficiency, depending on the problem.

Step 1: A parameter set, representing the physical properties of the materials found by experiment, is chosen and shown together with respective relative measurement errors in Table 1.

![Figure 3: General task scheme of a DEM algorithm.](image-url)
**Step 2**: Physical quantities such as positions $\mathbf{r}_i(t)$, velocities $\mathbf{v}_i(t)$, ... of all objects are set to their initial values: $\mathbf{r}_i(0) = \mathbf{r}_0$, $\mathbf{v}_i(0) = \mathbf{v}_0$, .... This is a very delicate task, since initial positions and velocities are generally not known in the spreading process. In some cases, however, one can apply a *random generator* to calculate the initial values. An example for this process is the filling of a bin with fertiliser grains.

**Step 3**: Contact detection is a demanding task in computational terms. In the simplest algorithm, direct contact detection, each particle has $(n-1)$ potential contact partners in a system of $n$ particles. Hence the computational effort would be at least proportional to $n^2$, where $n$ is the number of particles simulated. This algorithm should be avoided in large multi particle systems. The computation does not stop at this point however; when a potential candidate for a particle is found, a built-in algorithm searches if there is real contact. In general, this is a complex geometrical problem, except for spheres and planes. The process is also called *contact resolution*.

**Step 4**: A contact model calculates the forces between 2 particles. Force calculations are split in a normal and tangential direction to the particles’ surface. The choice of a contact force model is inherently dependent on the parameters (such as friction coefficients) which are determined experimentally.

**Step 5**: Integration of the equations of motion (1.1) will deliver the new generalized positions and velocities. A good integration algorithm is fast but conserves the total energy of the system. When non-spherical particles are introduced, due to the importance of orientation of the particles, more complex algorithms are required (see section 2.12.7).

**Step 6**: Increase the time: $t \rightarrow t + \Delta t$, where $\Delta t$ is the time step, or end the simulation.

### Single Particle Simulations

The main goal of this paragraph is to verify experimentally DEM simulations of single particle trajectories of fertilizer particles on a spinning disc. Fertiliser particles were dropped (from 0.025m height) on a flat steel disc (diameter 0.60m), containing two radial vanes (0.020m height 180° apart) and driven by an electromotor with adjustable rotational speed. Above the centre of the disc, a High Speed Camera was positioned facing downwards which records the particle’s trajectory at 500 frames per second (Figure 4).

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**Table 1**: measured parameters and relative measurement errors.

<table>
<thead>
<tr>
<th>Property</th>
<th>measurement RE (%)</th>
</tr>
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<tbody>
<tr>
<td>Radius (m)</td>
<td>6</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>7</td>
</tr>
<tr>
<td>Density (kg/m³)</td>
<td>3</td>
</tr>
<tr>
<td>Stiffness ($N/m^{2/3}$)</td>
<td>7</td>
</tr>
<tr>
<td>Restitution coefficient</td>
<td>2</td>
</tr>
<tr>
<td>External friction coefficient</td>
<td>1</td>
</tr>
</tbody>
</table>

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DEM simulations of the motion of a fertilizer particle on a spinning disc were compared with experimental trajectories. Results of a comparison between simulation and measurements are shown in Figure 5. DEM forces show in general very good agreement with experimental single particle trajectories despite some shortcomings of the experimental apparatus to characterize the initial position and velocity of the particle dropped on the spinning disc. Errors are found to be within 5 % at the end of the simulation.

Figure 4: Experimental set up for recording single particle trajectories. Left: the disc with the vanes, the particle holder, the high speed camera and the light source. Right: close-up of the disc showing the disc, the vanes and the holder.

Figure 5: Single particle trajectory expressed as the radial distance of the particle as a function of time. Experimental results are shown as a ° with an error bar indicating ± 2 times the standard deviation. The solid and the dashed line represent a simulated trajectories with initial velocity of 0m/s, and 0.14m/s respectively. The horizontal line represents the edge of the disc.
Multi particle simulations

The main objective of this chapter is to verify to which extend DEM is capable of predicting real spread patterns. A simulated spreader pattern was compared to a measured spreader pattern in a test hall. In order to make a comparison with DEM simulations feasible, the dimension of the experiments is kept low, and the number of particles is limited. Although the processing time of the experiments is not high (~5 s), simulation times are restricted to 2 s real time. As an example, Figure 6 represents a full 3D multi particle simulation of particles falling through the feeding bin on the spreader disc.

![Figure 6: Snapshot of a DEM simulation (for Type B disc): side view and top view.](image)

The experiment consisted of simulating and measuring a transverse static pattern (TSP). Baskets were aligned at a special distance described by the position vector (X,Y,Z) from the disc centre (Figure 7), where X is the transverse distance, Y is the longitudinal distance, and Z is the height between the baskets and the disc. By performing the TSP over different Y distances (when the tray is shifted incrementally over the total Y range), a total transverse spread pattern (TTSP) can be obtained. The disc is driven by a 1 kW electrical motor, and the rotational speed is monitored before each experiment.

![Figure 7: on the left: Scheme of the TSP experimental set up; on the right: aligned collector tray baskets for measuring the transverse spread pattern.](image)

The inside of the baskets is covered with a soft material to prevent that particles would jump out when impacting at high speed. The total length of the tray is 3.5m, which is equal to 16 baskets.
In Figure 8, a contour plot of the total area covered by the measured spread pattern is depicted for a disc rotational speed of 400 rpm. The total area covered by the measurements is 9 m² which resulted in 94% of the total particle mass used in the experiment. The rest fraction is missing due to particles that land beyond the basket area and the interpolation errors between the lines.

The pattern has a typical bended shape around the disc, with a high concentration zone in the front of the disc. Besides, an increase of density on the left side of the disc is observed. This smaller “peak” represents the particles changing direction by bouncing from contact with the vane edges and spill-over.

A number of experiments providing the transverse spread patterns of NPK fertilizer on a spinning disc with 0.15m radius and a rotational speed of 400 rpm and 300 rpm were carried out. Comparing with DEM simulations, the 300 rpm case was in good agreement. For the 400 rpm case, simulations still perform qualitatively well, but the errors were significantly larger. Generally, the experimental transverse spread pattern seems to cover a larger area in radial direction than the simulated, which is more concentrated on a smaller area.

Conclusion

The biggest concern of DEM simulations, nowadays, is the persisting lack of validation. This is mainly due to the restriction by computing power, resulting in simplifications or downscaling of the problem, and the difficulties that arise when summarizing the experiment.
This study provides valuable validated information about the outflow of the particles on the spinning disc. It was thereby possible to simulate a spreading pattern with sufficient agreement with a real spreading pattern.

As a general conclusion, we can state that DEM provides a powerful tool to model particle flows on a spinning disc. Although the results remain qualitative, they are able to give valuable information and insight in the search for improvement of fertilizer and spinning disc properties. This study shows as well the potential of DEM for a large variety of applications in granular handling.

The above work was conducted within the Discrete Element Group, lead by Dr. Bert Tijskens. The DEM research Group has more than 10 years experience in the development of DEM. Its home built DEMeter++ enjoys international reputation, due to its flexibility towards complexity and different applications.

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