

Simulation of mechano-technological processes of agro-industrial production using the discrete element method

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Abstract: Agriculture is a key sector ensuring food security and social stability, while reducing labor costs drives mechanization and automation of agro-industrial processes. Modern agricultural engineering requires systems engineering and computer modeling for effective equipment design. This study uses numerical modeling of mechanized processes via the Discrete Element Method (DEM) in Simcenter STAR-CCM+, enabling the development of physicomathematical models of interactions between machine components and bulk materials, including contact, elastic-damping, frictional, and cohesive forces. Numerical modeling with DEM allows identification of key operational patterns and parameter effects on process efficiency. Examples of mechanized processes include transportation (seed movement in a pneumatic seeder), dosing (seed metering in a photoelectronic separator), grinding (dehulling castor fruits and seed separation), pressing (granulated feed formation), mixing (blending feed components in a rotary mixer), and separation (seed mixture sorting in a trieur separator). These examples confirm the adequacy of the models, enabling identification of critical equipment points, implementation of changes at early design stages, and reduction of experimental time. The results demonstrate the value of modern digital engineering in agricultural machinery development and highlight its role in ensuring high levels of food security. By combining DEM modeling with advanced software, engineers can optimize mechanized processes, improve equipment performance, and support efficient, sustainable agro-industrial production.

Keywords: agro-industrial production, mechanization, numerical modeling, Discrete Element Method (DEM).

Citation: Aliiev, E. B. 2026. Simulation of mechano-technological processes of agro-industrial production using the discrete element method. *Agricultural Engineering International: CIGR Journal*, 28(3): 261-272.

1 Introduction

Agriculture is the foundation of social stability and food security in the state. The need to reduce labor costs has promoted the mechanization and automation of agro-industrial production. Agricultural engineering continuously develops and applies new technologies.

As noted in studies (Khan et al., 2021; Sultan, 2024; Ahmed and Miller, 2022), systems engineering in agricultural machinery is impossible without

design preparation, which includes the development of new machines and the modernization of existing ones, identification of technological process patterns, and the development of physico-mathematical models of interactions between working components and multiphase media.

Modern research on mechanical and technological processes (Kulazhanov et al., 2021; Aliiev, 2019; Shevchenko, 2016) often relies on analytical methods, leading to complex systems of differential equations

Received date: 2025-10-04 **Accepted date:** 2026-04-14

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that are practically unsolvable by traditional approaches, creating a need for numerical modeling (Aliiev, 2023). Engineering of technical systems is impossible without modern CAD/CAE methods and software (Lyashenko et al., 2021). Using numerical modeling in the design of agricultural machinery allows for the detection of collisions and inconsistencies at early stages, creation of virtual prototypes, and reduction of material costs (Obstbaum et al., 2017; Montgomery, 2013; Jenkins, 2017). The CAE software Simcenter STAR-CCM+ enables high-level scientific research, reducing the time required for preparation and experimentation through numerical modeling of processes on a computer (Aliiev, 2023).

The aim of this work is to improve the efficiency of mechanized processes in agro-industrial production through preliminary numerical modeling using the Discrete Element Method (DEM) based on developed scientific and methodological principles.

2 Methodology

The generalized methodology for conducting numerical modeling includes the following stages (see Figure 1): concept (design and technological scheme) of a technical device (working body); determination of the main geometrical dimensions of the technical device (working body); creation of a 3D model of the technical device (working body) in a CAD system; determination of the physical and mechanical properties of the medium interacting with the technical device (working body); technological process analysis; creation of a model in a CAE system; determination of numerical modeling factors; determination of numerical modeling criteria; planning of a numerical experiment; conducting the modeling; correlation, variance, and regression analyses of the modeling results; statistical analysis of the adequacy of the obtained modeling results.

The interaction of agricultural machine working components with granular materials (seeds, feed, fertilizers, soil, etc.) can be modeled using the DEM.

The Johnson–Kendall–Roberts (JKR) DEM model extends the Lagrangian approach for dense particle flows by including contact forces in the equations of motion. Simcenter STAR-CCM+ applies classical mechanics and the Hertz–Mindlin elastic-damping contact model, where the contact force depends on particle overlap, their physical and mechanical properties, and particle sizes.

To determine the contact interaction force between particles using the DEM method, an appropriate computational scheme has been developed (see Figure 2).

In DEM, the rotational and translational movements of individual particles are determined by applying Newton's second law at each time step using the following equations:

$$\begin{aligned} m_i \frac{d\bar{v}_i}{dt} &= \sum_j (\bar{F}_{ij}^n + \bar{F}_{ij}^t) + m_i \bar{g} \\ I_i \frac{d\bar{\omega}_i}{dt} &= \sum_j (\bar{R}_{ij} \times \bar{F}_{ij}^t - \bar{\tau}_{ij}^r) \end{aligned} \quad (1)$$

Where,

m_i – particle mass, kg;

I_i – moment of inertia, kg·m²;

v_i – translational velocity of the particle, m s⁻¹;

ω_i – angular velocity of the particle, s⁻¹;

g – gravitational acceleration, m s⁻²;

F_{ij}^n, F_{ij}^t – normal and tangential forces applied to particle i due to interaction with particle j , N;

τ_{ij}^r – rolling resistance moment applied to particle i due to interaction with particle j , N·m;

R_{ij} – vector from the center of mass of particle i to the contact point with particle j , m.

The tangential and normal contact forces (F_{ij}^t and F_{ij}^n), are represented using the linear elastic-damping Hertz–Mindlin model (Capozzi et al., 2019), incorporating both elastic and viscous contributions (see Figure 2a). In this model, the normal and tangential forces have elastic and viscous components, denoted by the indices e (elastic) and v (viscous), and are decomposed according to the following equations:

$$\bar{F}_{ij}^n = \bar{F}_{ij}^{ne} + \bar{F}_{ij}^{nv}, \quad \bar{F}_{ij}^t = \bar{F}_{ij}^{te} + \bar{F}_{ij}^{tv} \quad (2)$$

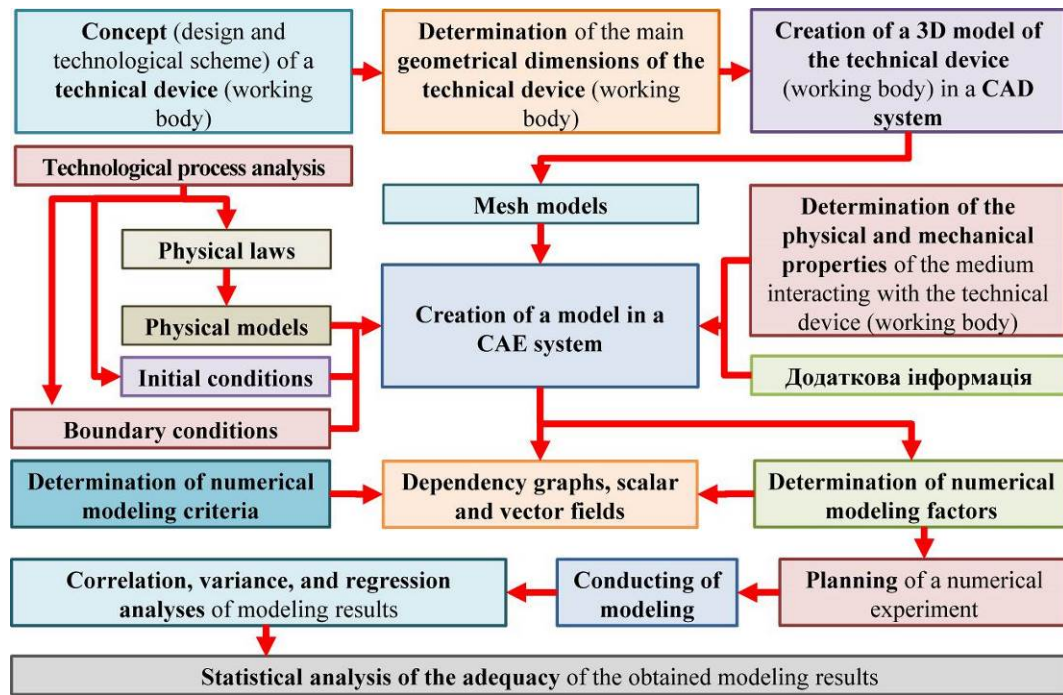
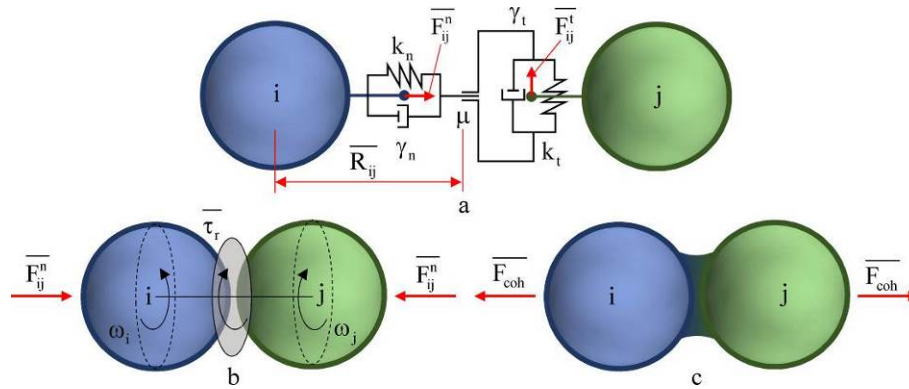


Figure 1 Generalized methodology for conducting numerical modeling



(a) Hertz-Mindlin model; (b) constant-direction torque rotational friction model (CDT); (c) simplified Johnson-Kendall-Roberts cohesion model (SJKR)

Figure 2 Generalized DEM contact models

In addition, the tangential force is determined according to Coulomb's friction law $\overline{F_{ij}^t} \leq \mu \overline{F_{ij}^n}$, where μ is the coefficient of friction. If this value is exceeded, sliding occurs between particles. The normal elastic force (F_{ij}^{ne}) is derived from Hertz's classical theory of contact between two spheres (Johnson, 1987), which assumes small elastic deformations, limited contact areas, and an ellipsoidal stress distribution at the contact interface.

The tangential elastic force (F_{ij}^{te}) is formulated according to Mindlin's theory (Chen and Kumar, 2013) and is a function of both the normal and tangential overlaps, (δ_n) and (δ_t), respectively. The tangential overlap (δ_t) results from the relative

tangential velocity between the two particles at the contact point. These models capture the nonlinear relationship between normal elastic forces and particle displacements:

$$\begin{aligned} \overline{F_{ij}^{ne}} &= -k_n \overline{\delta_n} = \frac{4}{3} E^* \sqrt{R^*} |\overline{\delta_n}| \overline{\delta_n} \\ \overline{F_{ij}^{te}} &= -k_t \overline{\delta_t} = 8G^* \sqrt{R^*} |\overline{\delta_n}| \overline{\delta_t} \end{aligned} \quad (3)$$

Where,

k_n, k_t – normal and tangential contact stiffness, N m^{-1} ;

$R^* = R_i R_j / (R_i + R_j)$ – equivalent radius of two contacting bodies, m;

R_j – radius of particle j, m;

$G^* = (2(2 - \nu_i)(1 + \nu_i)/E_i + 2(2 - \nu_j)(1 + \nu_j)/E_j)^{-1}$ – equivalent shear modulus, Pa;

$E^* = ((1 - \nu_i^2)/E_i + (1 - \nu_j^2)/E_j)^{-1}$ – equivalent Young's modulus, Pa;

ν_i – Poisson's ratio of particle i;

E_i – Young's modulus of particle i, Pa.

The viscous terms in the model enable energy dissipation, allowing the system to stabilize and reach a compacted state within a finite time. In the original approach (Chen and Kumar, 2013), the critical damping coefficient (β) was defined using the critical damping time of a spring–mass–damper system with a single degree of freedom. In Rahimi-Larki et al. (2024), it was proposed that (β) can instead be expressed through the restitution coefficient e , which characterizes particle energy loss during impact and plastic deformation $\beta = -\ln(e)/\sqrt{\ln(e)^2 + \pi^2}$. Under the condition $\beta = 1$, the system is critically damped, achieving equilibrium compaction in the minimum possible time.

$$\begin{aligned}\overline{F_{ij}^{nv}} &= -\gamma_n \overline{v_n} = -2\sqrt{5/6}\beta\sqrt{S_n m^* v_n} \\ \overline{F_{ij}^{nt}} &= -\gamma_t \overline{v_t} = -2\sqrt{5/6}\beta\sqrt{S_t m^* v_t}\end{aligned}\quad (4)$$

Where,

γ_n and γ_t – viscoelastic damping coefficients in the normal and tangential directions, respectively, $N \cdot s \cdot m^{-1}$;

v_t, v_n – the tangential and normal parts of the relative velocity at the point of contact, $m \cdot s^{-1}$;

$m^* = m_i m_j / (m_j + m_i)$ – equivalent mass, kg;

$$S_n = 2E^* \sqrt{R^* |\delta_n|}, \quad S_t = 8G^* \sqrt{R^* |\delta_n|} \quad -$$

normal and tangential stiffness, $N \cdot m^{-1}$.

Several rolling resistance models exist (Rahimi-Larki et al., 2024; Liu et al., 2011); however, the Constant Directional Torque (CDT) model is among the most widely used in DEM studies due to its relative accuracy and computational efficiency. In this approach, the resistive torque (τ_{ij}^r) is assumed to be proportional to the normal force (F_{ij}^n) and acts

along the direction of relative rolling $\overline{\omega_{ij}}/|\overline{\omega_{ij}}|$. Its expression is as follows (see Figure 2b):

$$\overline{\tau_{ij}^r} = -\mu_r R^* \left| \overline{F_{ij}^n} \right| \times \overline{\omega_{ij}}/|\overline{\omega_{ij}}| \quad (5)$$

Where,

μ_r – rolling friction coefficient;

ω_{ij} – the angular velocity of particle i relative to particle j, s^{-1} .

To simulate the bonds between particles arising from sintering, an additional cohesive model shown in Figure 2, c is considered. The Johnson–Kendall–Roberts (JKR) model (Style et al., 2013) accounts for adhesion by incorporating an additional normal force, known as the pull-off force, which ensures particle contact is preserved. In the simplified JKR (SJKR) approach, the cohesive force is determined according to the following expression:

$$|\overline{F_{coh}}| = \Omega \pi a^2 \quad (6)$$

Where,

Ω – cohesive energy density normalized by volume, $J \cdot m^{-3}$;

a – contact region of circular shape, m^2 .

The presented Equations 1–6 fully describe the translational and rotational motion of particles under contact interaction, including elastic, viscous, frictional, rolling resistance, and cohesive forces. The described DEM scheme is a reliable tool for analyzing mechanical and technological processes in granular systems, allowing optimization of equipment design, process parameters, and material handling strategies in agro-industrial production.

Therefore, the described equations and contact models form the core of the physical–mathematical framework underlying the Simcenter STAR-CCM+ software, which serves as a tool for numerical simulation of mechanical and technological processes.

3 Results and discussion

Mechanized processes of agro-industrial production can be classified according to the nature of the mechanical action on raw materials and products.

Such systematization makes it possible to distinguish the main groups of operations that define technological production schemes and ensure processing efficiency.

Transportation and dosing processes provide the movement of raw materials, semi-finished, and finished products between individual operations and units, as well as accurate measurement of required component quantities. These include conveyors (belt, screw, scraper, pneumatic); elevators and bucket conveyors; dosers (volumetric, weight-based, screw, vibratory). Their main task is to ensure continuity of the production flow and uniform material feed.

Processes of grinding and pressing are aimed at changing the size, shape, and structure of materials to facilitate further processing or obtain the final product. These include crushers (hammer, roller, jaw, cone); mills (disk, ball, rotor); presses (screw, hydraulic, roller). Grinding increases the specific surface of raw materials to intensify physico-chemical processes, while pressing is used for oil or juice extraction or feed pellet formation.

The purpose of mixing and separation processes is to form homogeneous mixtures or, conversely, to divide heterogeneous systems into components.

Mixing is carried out in mixers (paddle, screw, drum, planetary, V-type), ensuring uniform distribution of components. Separation involves removing impurities or fractionating materials by mass, size, shape, or other properties. Equipment used includes separators, aspirators, sieving and brushing machines, magnetic and optical sorters. These processes are crucial for achieving the required quality of the final product, especially in food and feed mix production.

Based on this systematization, numerical modeling of the mentioned operations was carried out using modern computer simulation methods. The study considered the specific features of equipment operation and particle interaction. This provided a detailed understanding of transportation, dosing, grinding, pressing, mixing, and separation processes. The obtained results will be further analyzed to identify characteristic patterns and determine optimal operating modes of machines and devices.

The problem of seed transportation in the feeding system of a pneumatic precision seed drill is shown in Figure 3. The seeding unit consists of a seed boot, single disc furrow opener, seed tube, seed lock wheel, seed flap, and seed brake.

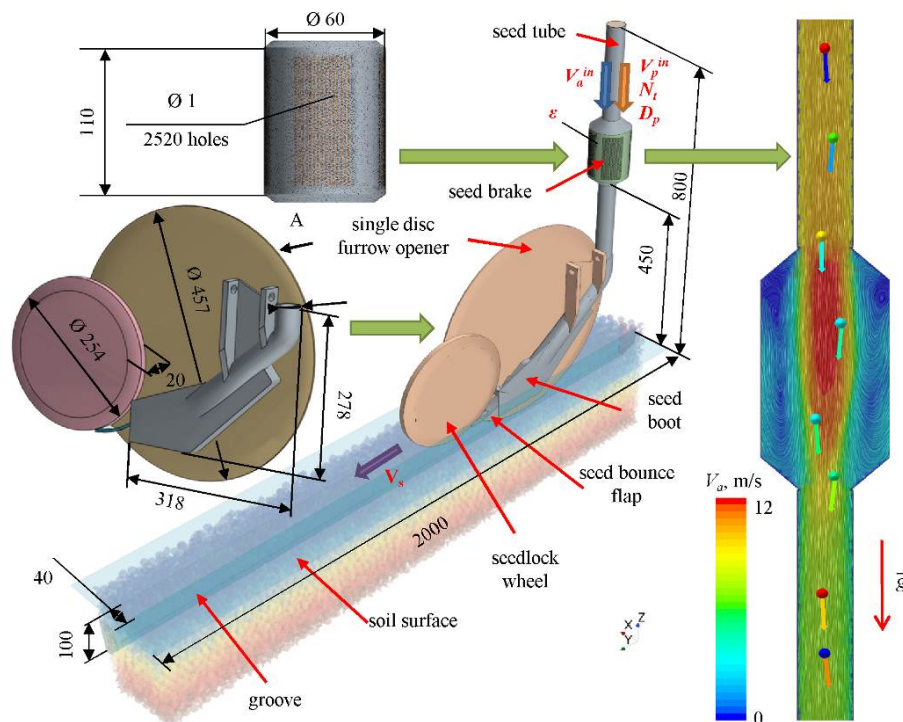


Figure 3 Scheme of numerical modeling of the seeding unit operation process of a pneumatic seeder

As mesh models, the following were selected: polyhedral cell generator, surface mesh generator, and extruder. The reference parameters of these generators are as follows: base size – 0.004 m; surface growth rate – 1.3; relative minimum size for cell refinement – 10%; minimum allowable face quality – 0.001 m. As physical models, the following were chosen: ideal gas model (air), k- ϵ turbulence model, segregated flow model, Lagrangian multiphase model, specifically the DEM for representing seeds with consideration of multiphase interactions among themselves and with the wall, and two-way DEM–CFD coupling. The simulation of the process was performed in three-dimensional space with an unsteady implicit solver. Time step – 0.01 s. Total simulation time – 1200 s. For air, the following physical and mechanical properties were used: dynamic viscosity – $1.85 \cdot 10^{-5}$ Pa·s; turbulent Prandtl number – 0.9; molecular weight – 28.96 kg kmol⁻¹. As a model of pea seeds, continuous spherical DEM particles with constant density were adopted: effective diameter – 0.008 m; density – 1180 kg m⁻³; Poisson's ratio – 0.32; Young's modulus of elasticity – 70 MPa. For seed-to-seed interactions, the

following values were set: static friction coefficient – 0.52; normal and tangential restitution coefficients – 0.3; rolling friction coefficient – 0.001; no linear cohesion. For seed-to-steel wall interactions, the following were applied: static friction coefficient – 0.41; normal and tangential restitution coefficients – 0.5; rolling friction coefficient – 0.001; no linear cohesion. Cohesion is absent.

Through numerical simulation of the seed retarder in a pneumatic seed drill using the Simcenter STAR-CCM+ software, the movement of seeds and the airflow within the retarder's working zone were visualized.

The analysis of the obtained data made it possible to determine how the seed velocity at the outlet of the decelerator (V_{pout}) and the coefficient of variation of the seeding rate (η) depend on the airflow velocity at the inlet (V_{ain}) and the ratio of the outlet to inlet cross-sectional areas (ϵ). The corresponding dependencies for the model and the laboratory experiment are shown in Figure 4. The NRMSE < 6.3%, and the correlation coefficient between the model and experimental dependencies is 0.943.

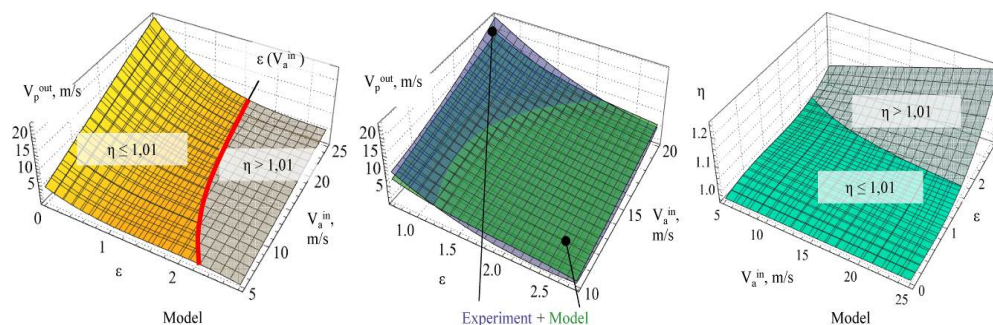


Figure 4 Results of numerical modeling and laboratory experiments of the operation process of the pneumatic seeder metering device

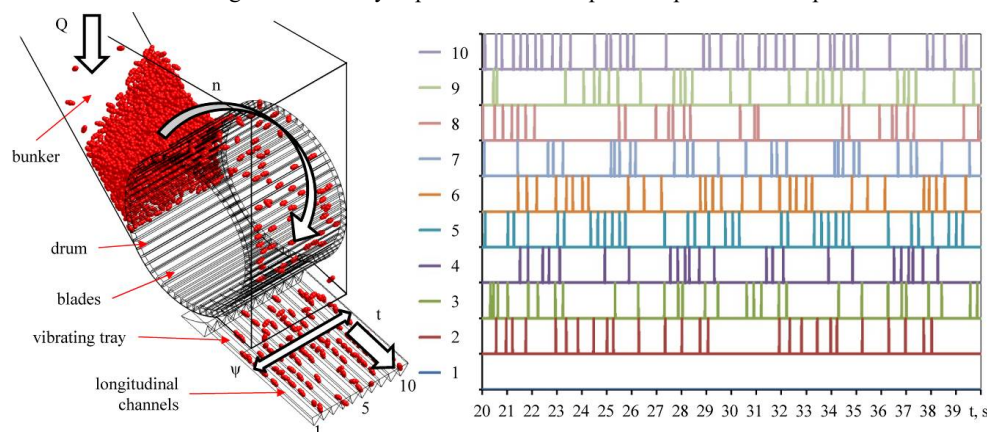


Figure 5 Scheme of numerical modeling of the seed feeding unit operation of a photoelectric separator

The problem of seed dosing in the seed feeding unit of a photoelectronic separator is shown in Figure 5. The seed feeding unit consists of a bunker, drum, blades, vibrating tray, and longitudinal channels. The mesh and physical models, as well as the physical and mechanical properties and boundary conditions for this problem, were chosen to be the same as for the pneumatic seeder problem.

Numerical simulation of seed motion under the influence of the feeding unit's working mechanism in

the photoelectronic separator, performed in Simcenter STAR-CCM+, enabled the development of a physico-mathematical model that relates the mean time interval between falling seeds (t) to the seed feed rate (Q), the vibration tray frequency (ψ), and the drum rotation speed (n). The corresponding dependencies for the model and the laboratory experiment are shown in Figure 6. The NRMSE $< 5.6\%$, and the correlation coefficient between the model and experimental dependencies is 0.926.

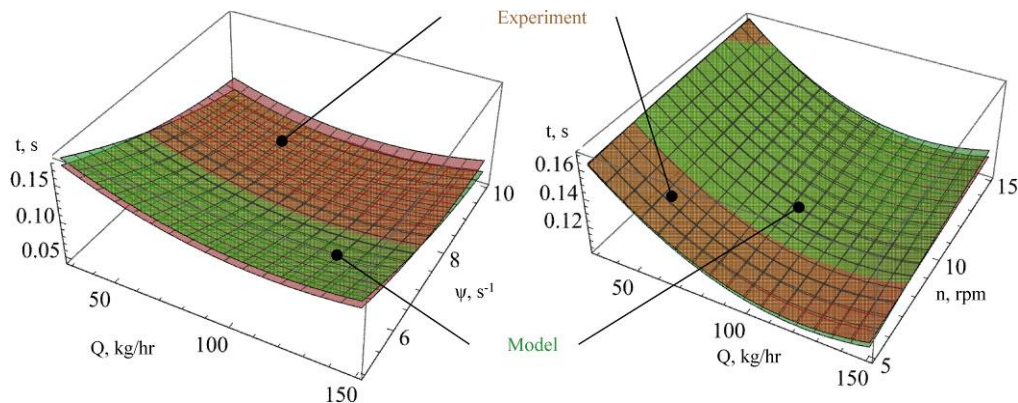


Figure 6 Results of numerical simulation and laboratory experiment of the feeding unit mechanism operation in the photoelectronic separator

The problem of crushing (dehulling) castor fruits and separating the seeds in the corresponding machine is shown in Figure 7. The main working bodies of the machine are the crushing cone and the reverse cone. The mesh and physical models were chosen the same as for the pneumatic seeder problem. However, the fruits were represented as agglomerates of spherical particles, and their interaction followed the linear cohesion model. The diameter of the constituent particles of a fruit was 3 mm, the fruit diameter – 15 mm, Poisson's ratio – 0.35, Young's modulus – 15 MPa, specific cohesive energy per unit volume – 1000 J m^{-3} , and the tensile and shear strength limit – 2 MPa. Other physical-mechanical properties and boundary conditions for this problem were taken the same as for the pneumatic seeder problem. Numerical modeling of the process of castor fruit and seed destruction under compressive load, carried out based on the scheme (see Figure 7) with consideration of the physical-mechanical and rheological properties of the biomaterial, made it

possible to analyze in detail the stages of deformation and fracture of these objects.

Numerical simulation of the castor seed separation process allowed determination of how the fraction of unhulled seeds (segments) (ξ_f), depends on the spacing between the reverse and crushing cones (δ), the rotation speed of the crushing cone (n), the feed hole diameter (D_{in}), and the inclination angle of the crushing cone axis (γ). The corresponding dependencies for the model and the laboratory experiment are shown in Figure 8. The NRMSE $< 9.2\%$, and the correlation coefficient between the model and experimental dependencies is 0.895.

The problem of feed pellet pressing in the corresponding granulator is shown in Figure 9. Per the design specifications, the granulator model includes a cylinder, piston, cone, and crown nuts. Numerical simulation of the feed granulator's forming die enabled determination of the dynamics and spatial distribution of the feed mixture components within the die under applied pressure.

The mesh and physical models were chosen the same as for the fruit destruction problem. The physico-mechanical properties of the feed mixture components were set as follows: static friction coefficient – 0.62, density – 710 kg m^{-3} , tangential restitution coefficient – 0.6, normal restitution

coefficient – 0.6, effective particle diameter – 0.5 mm, Young's modulus – 22.3 MPa, Poisson's ratio – 0.31, cohesion work per unit area – 0.49 N m^{-1} . The time step was 0.01 s, with 5 iterations per time step. The exposure time was 4 s, and the piston displacement speed was 0.01 m s^{-1} .

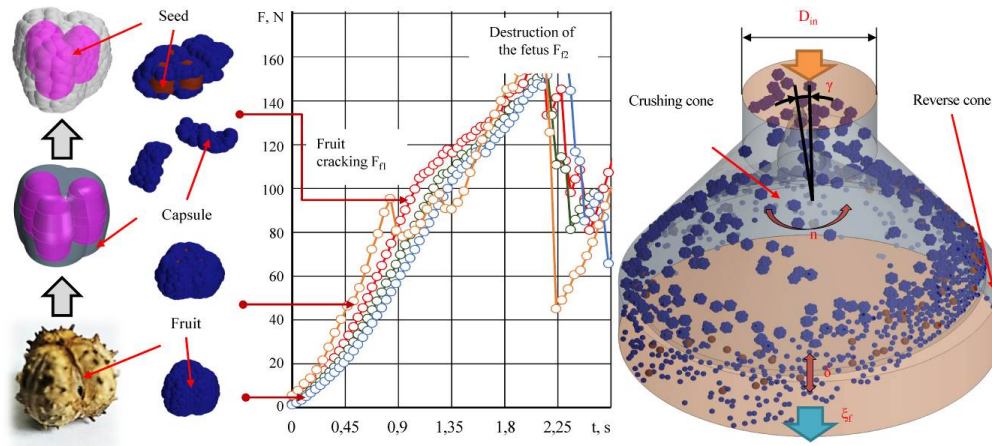


Figure 7 Scheme of numerical modeling of the castor seed cleaning machine operation

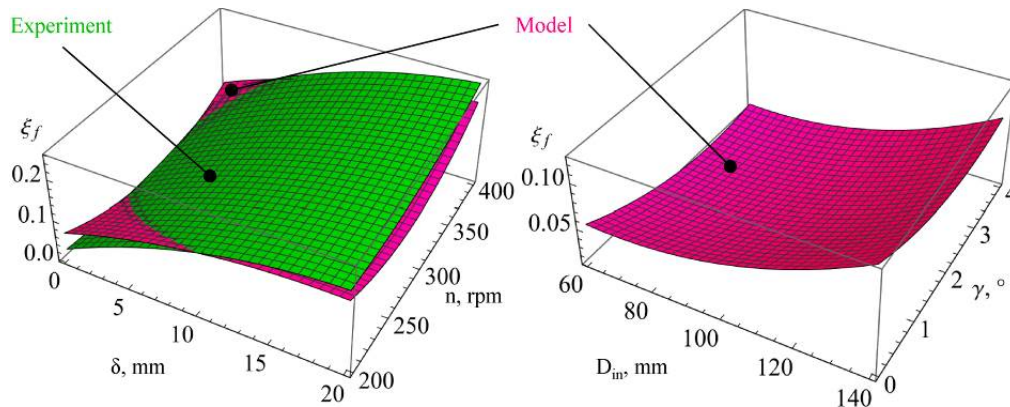


Figure 8 Results of numerical simulation and laboratory experiment of the castor fruit cleaning machine operation

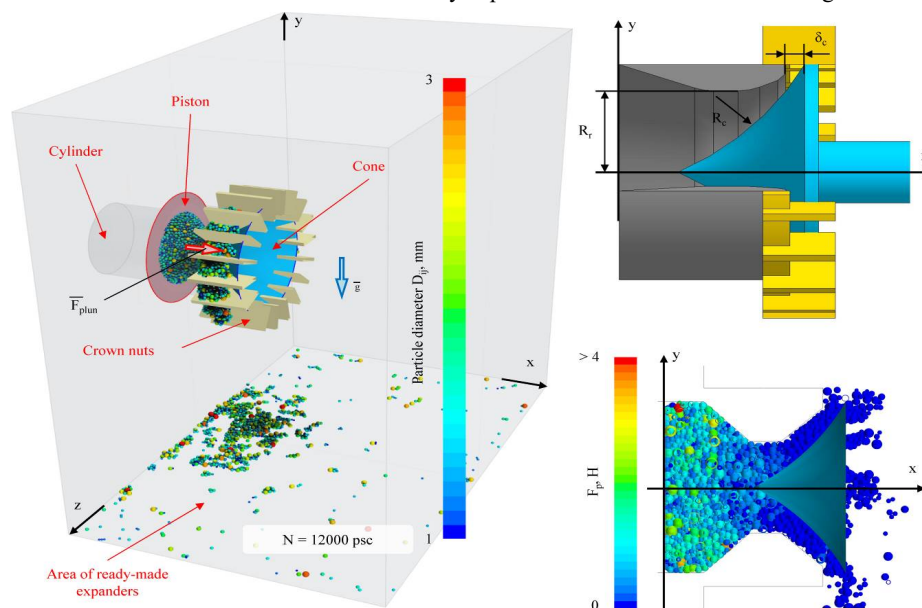


Figure 9 Diagram and findings from the numerical simulation of the feed granulator's operation

The relationship was determined between the density of the obtained granules (ρ) and the compression radius of the matrix cylinder (R_r), the radius of the concave cone (R_c), and the clearance between the cone and the cylinder (δ_c). The corresponding dependencies for the model and the laboratory experiment are shown in Figure 10. The NRMSE < 4.3%, and the correlation coefficient between the model and experimental dependencies is 0.951.

The problem of mixing feed components in the corresponding mixer is shown in Figure 11. The feed mixer consisted of a cylinder and blades installed at a specified angle. The following mesh models were selected: trimmer and surface mesh generator. The base mesh size was 0.01 m.

The following physical models were chosen: three-dimensional, unsteady implicit, gas (air), segregated flow, gradients, constant density, laminar, Lagrangian multiphase, DEM, multiphase interaction, and gravity. For the Lagrangian phase, two components were defined with the following models: DEM particles, pressure gradient force, spherical particles, continuum, constant density, and lifetime. All possible interactions between components and with the domain walls were created. The following interaction models were selected: DEM phase interaction, Hertz–Mindlin, and rolling resistance. Physico-mechanical properties of the components were: Poisson's ratio – 0.45, Young's modulus – 517,000 Pa, density – 800 kg m⁻³. Particle diameter – 0.003 m. Solver parameters: time step – 0.01 s; maximum physical time – 16 s.

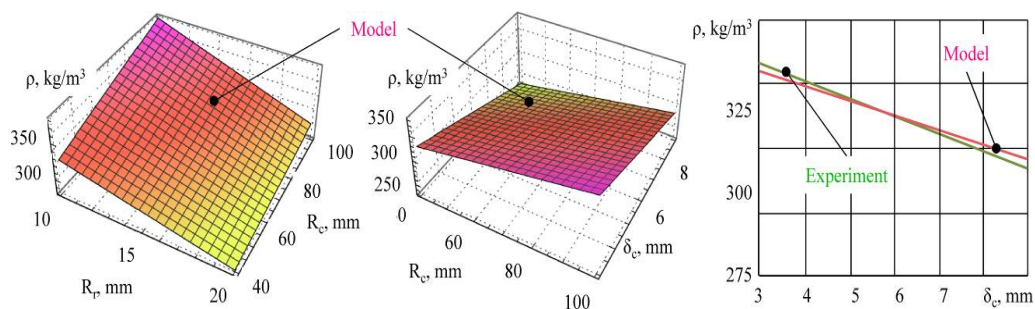


Figure 10 Results of numerical modeling and laboratory experiments of the feed pelletizer operation process

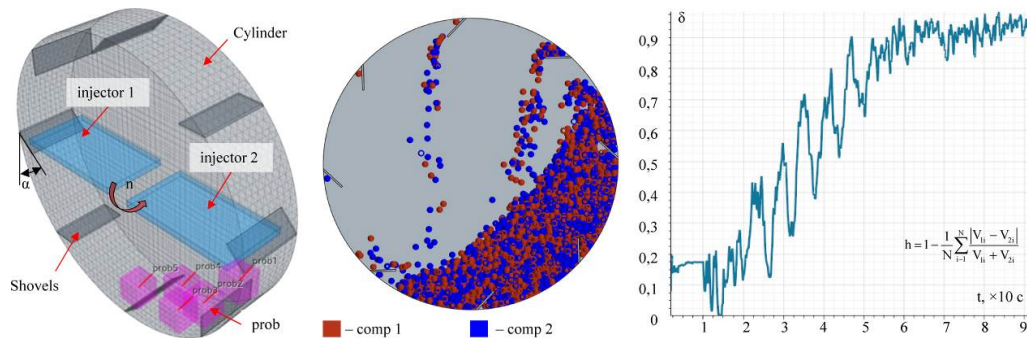


Figure 11 Numerical simulation setup and findings for the feed mixer's performance

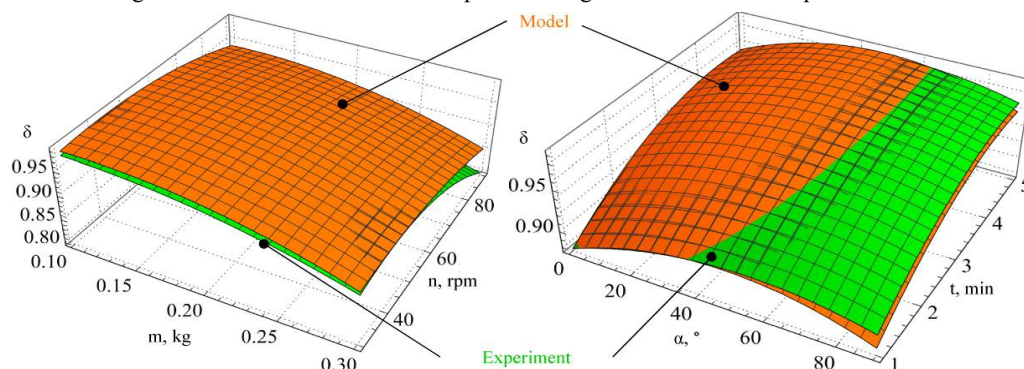


Figure 12 Results of numerical simulation and laboratory experiments on the operation of feed mixers

Numerical simulation of the periodically operating rotary mixer–feeder provided insight into the kinetics of the mixing process, allowing determination of how the mixture homogeneity coefficient (δ) changes depending on the blade inclination angle (α), material mass (m), rotation speed (n), and mixing time (t). The corresponding dependencies for the model and the laboratory experiment are shown in Figure 12. The NRMSE < 6.9%, and the correlation coefficient between the model and experimental dependencies is 0.933.

The problem of seed separation on a trieur separator is shown in Figure 13. The trieur separator consists of a cylinder with cells and a tray. The mesh

and physical models were chosen the same as in the mixing simulation. The mixture components consisted of mustard seeds in the form of spheres and impurities (elongated in shape) as agglomerates of particles. The physico-mechanical properties of the components were taken as identical: Poisson's ratio – 0.5, Young's modulus – 0.2 MPa, density – 700 kg m⁻³, static friction coefficient – 0.8, normal restitution coefficient – 0.5, tangential restitution coefficient – 0.5, rolling resistance coefficient – 0.1. The effective diameter of seeds (and impurities) followed a normal distribution: mean value – 2 mm (3 mm), and standard deviation – 1 mm.

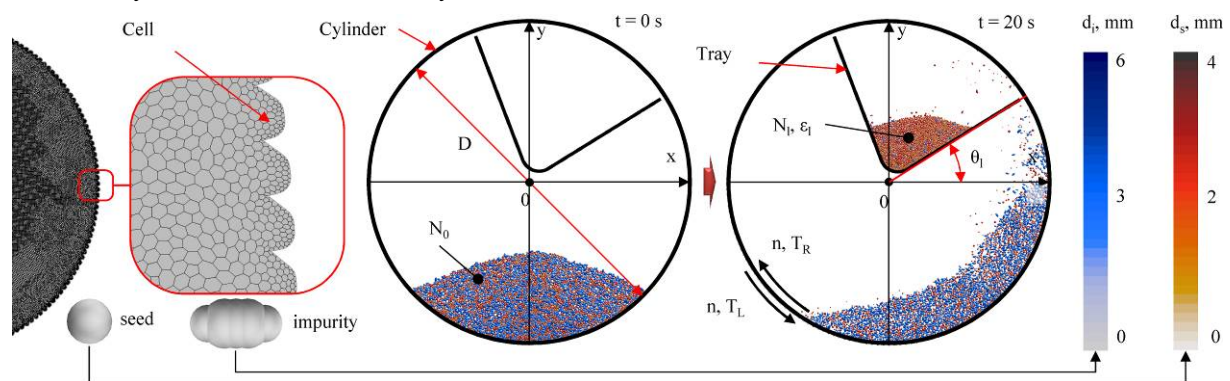


Figure 13 Scheme and results of numerical modeling of the trieur separator operation process

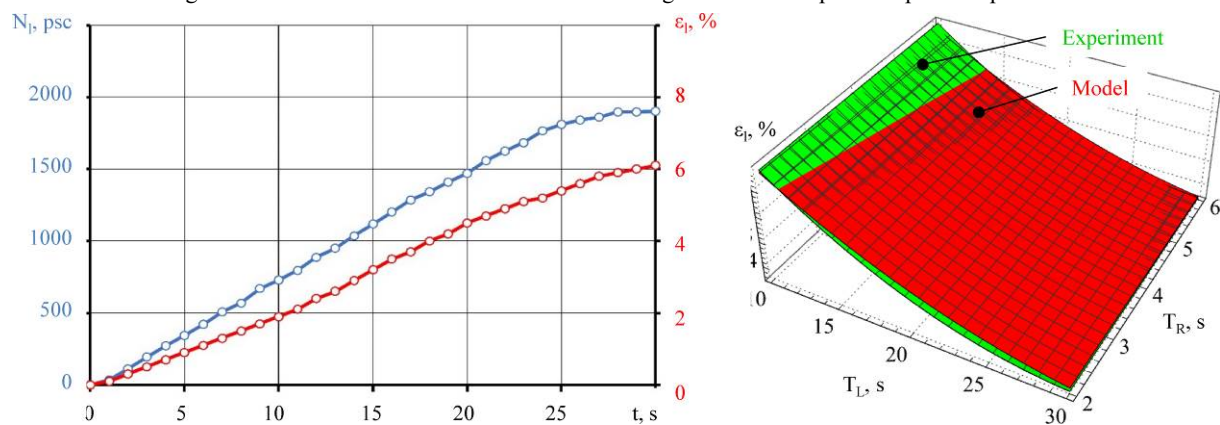


Figure 14 Results of numerical simulation and laboratory experiments on the operation of a selective triage separator

Numerical simulation of the mustard seed separation process using a selective triage separator at different rotation speeds allowed analysis of the dynamics of seeds and impurities (N_i), as well as the relative impurity content (e_i) in the seed mixture within the tray. In addition, the simulation provided relationships between the relative impurity content (e_i) and the cylinder rotation duration clockwise (T_R) and

counterclockwise (T_L). The corresponding dependencies for the model and the laboratory experiment are shown in Figure 14. The NRMSE < 9.2%, and the correlation coefficient between the model and experimental dependencies is 0.875.

The conducted numerical modeling of mechanized processes in agro-industrial production allowed obtaining a detailed understanding of the

interaction between the working bodies of technical devices and bulk materials, confirming the effectiveness of the DEM in modern agricultural machinery engineering. The results showed that numerical modeling not only makes it possible to predict material behavior during transportation, grinding, pressing, mixing, and separation, but also to optimize the structural and technological parameters of equipment.

It is important to note that although DEM numerical modeling provides high accuracy in predicting the behavior of bulk materials, certain limitations exist. These include the need for precise determination of the material's physical-mechanical properties, constraints on model size due to computational resources, and simplifications of contact models for multiparticle systems. Further research may focus on improving cohesion and friction models, accounting for the effects of moisture and material heterogeneity, and integrating DEM with other numerical modeling methods for multiphase processes.

Thus, the study results demonstrate the significant potential of using modern CAE systems (Simcenter STAR-CCM+) for the design and optimization of agricultural machinery. The application of these approaches allows reducing the time and costs of experimental testing, increasing the accuracy and efficiency of mechanized agro-industrial processes, and promoting the development of scientific methods in agricultural machinery engineering.

4 Conclusions

The study of mechanized processes in agro-industrial production using numerical modeling with the DEM method and the Simcenter STAR-CCM+ software package enables the identification of key patterns in equipment operation and the influence of parameters on process efficiency. The presented examples of mechanized agro-industrial processes – namely, transportation (movement of seeds in the seeding section of a pneumatic seeder), dosing (seed

dosing in the seed feeding unit of a photoelectronic separator), grinding (dehulling castor fruits and separating seeds in the corresponding machine), pressing (formation of feed pellets in a granulator), mixing (mixing feed components in a rotary mixer), and separation (division of a seed mixture in a trieur separator) – confirm the adequacy of the physico-mathematical models. These studies also allow identifying critical points in equipment operation, implementing necessary modifications at early design stages, and reducing the time required for experimental research. The obtained results emphasize the importance of modern digital engineering for the development of agricultural machinery and the achievement of a high level of food security.

Scientific novelty of the study (proposed for the first time):

- a generalized DEM-based methodological framework for modeling mechanized agro-industrial processes has been developed, integrating all stages from CAD design to CAE simulation, parametric analysis, and statistical validation;

- a unified systematization of agro-industrial processes (transportation, dosing, grinding, pressing, mixing, separation) has been proposed from the perspective of DEM applicability, identifying common modeling principles;

- a structured approach to selecting simulation criteria, input parameters, and performance indicators has been formulated for consistent comparison of different types of equipment;

- a procedure for integrating DEM simulation results with experimental validation (NRMSE and correlation analysis) has been formalized.

Adapted and implemented known approaches (Simcenter STAR-CCM+ and DEM theory):

- particle interactions are modeled using standard DEM contact laws implemented in Simcenter STAR-CCM+, including Hertz–Mindlin, Coulomb friction, CDT rolling resistance, and JKR/simplified JKR cohesion models;

– CFD–DEM coupling, k – ε turbulence modeling, and the Eulerian–Lagrangian framework are applied in their standard software implementation;

– classical mechanics relations (Hertz, Mindlin, Newton’s laws) are used without modification as the theoretical basis of particle motion.

Practical advantages of DEM-based simulation:

DEM modeling enables early-stage virtual testing of agricultural machinery, reducing prototyping time and experimental costs. It provides detailed insight into particle–machine interactions, allows identification of critical flow regimes and inefficient zones, and supports optimization of design and operating parameters. Integration with CFD/CAE tools such as Simcenter STAR-CCM+ enhances the accuracy, efficiency, and resource-saving potential of agricultural equipment design.

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