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Validation of a particle simulation of potato tubers under harvesting-like conditions

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In order to optimise potato harvesting processes, particle simulations are capable of reducing the number of extensive experiments in the field. With the commonly used Discrete Element Method (DEM), it might be possible to get a deep insight into potato handling processes. The implementation of DEM models requires information about the material behaviour and shape of the particles as well as information about the interaction between particles and machine elements. Therefore, the first step consists of building a model representing an idealised potato tuber. The second step is creating a contact model capable of reproducing the target model abilities. The contact parameter can be defined by using small-scale tests. In order to test the model capabilities, the last necessary step is a validation test under realistic "harvesting-like" conditions. This paper proves a potential way to validate essential model behaviour in a single validation process.

Keywords
Discrete element method, validation, potato tuber, harvest process, material flow, impact behaviour

The potato is an important food source with a worldwide production of 376.8 mio t in 2016 (FAO 2018). Compared to other carbohydrate supplying staple foods, such as cereals, potatoes need to be undamaged for storage and marketability (Peters 1996). Tuber damage is mainly caused by unsuitable harvesting machine settings and discharging into or out of trailers, increasing with drop height. The importance of reducing tuber damage is taken into account in the development of new and optimised harvesting processes. Field tests to verify the improvements of new systems are only possible in late development stages and therefore expensive and time-consuming. By simulating the material flow through the machine in early stages the amount of field-test and development time could be reduced. Validation of the particle simulation model under controlled conditions is necessary to show the model capabilities. Therefore, the validation process needs to be matched to model requirements for the specific application.

Development of the simulation model

The Discrete Element Method (DEM) is widely used to simulate discontinuous materials. Due to free moving particles in three-dimensions and their defined interactions through contact models, the DEM is increasingly used in agricultural engineering (Lenaerts et al. 2014, Thielke et al. 2015, Kovács et al. 2016).

The DEM simulation differentiates between particles, representing the material flow and geometry elements often representing machine parts and limiting the simulation domain. Geometry elements have defined positions and only move on predefined paths. At each simulation time step, the contact forces between interacting particles and between particles and geometry elements are calculated for

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each particle. To complete the time step, the particles are moved, corresponding to Newton's laws of motion, to their new position resulting in a change in the interactions (Figure 1).

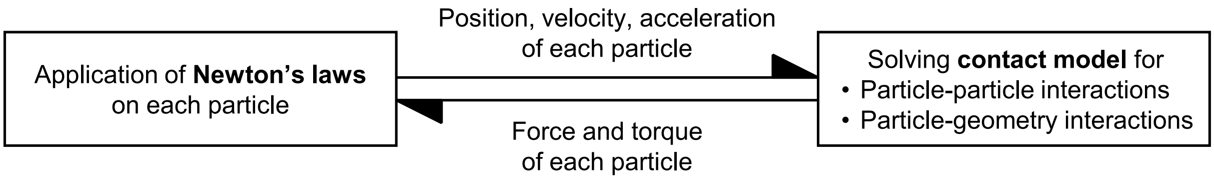


Figure 1: Simplified DEM calculation cycle

For optimisation of potato harvesting processes, the material flow and the individual impact behaviour are the most relevant characteristics. An accuratly modelled material flow can be used to increase process efficiency and quality. An appropriate impact behaviour is necessary to detect and reduce potato harming incidents in the harvesting process. With the DEM, these characteristics are related to and defined by the contact model. Like most agricultural material, potato tubers have viscous and elastic material properties. To implement this viscoelastic behaviour, the commonly used EDEM Hertz-Mindlin (no slip) contact model by DEM Solutions (2019) is used, as shown in Figure 2. The normal spring force is based on the Hertzian contact theory (Hertz 1882) and the tangential spring force is based on Mindlin et al. (1953). Tsuji (1992) developed the submodel for the damping forces in normal and tangential direction. Cundall et al. (1979) implemented the friction element based on the coulomb friction model. The contact stiffness k_i and damping d_i in normal as well as in tangential direction depend on the Young's Modulus (YM) and coefficient of restitution (COR). The tangential forces are limited by a static friction element μ to allow slippage.

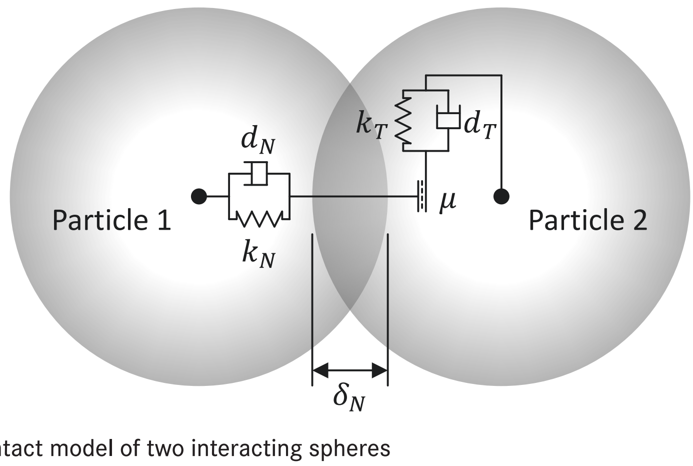


Figure 2: Viscoelastic contact model of two interacting spheres

As shown in previous research by Bajema et al. (1998 a), Geyer et al. (2009) and Diels et al. (2016), the apparent YM and COR of fruit depend on various factors and are not as constant as for example steel. Therefore, the adapted contact model, shown in Figure 3, uses specific information of the interacting particles at the first contact to calculate individual contact YM and COR. The individual contact parameters are stored and remain unchanged for the next calculation cycles. At the end of the contact, the individual YM and COR are discarded and, in case of a second contact, recalculated. With these individual YM and COR for each contact the simulation model can achieve comparable viscoelastic material behaviour to the measurements with real potato tubers. This concept for the contact model has shown to be functional. The contact model used in this research has been revised and improved after analysing its sensitivity on different contact parameters, leading to an optimised impact behaviour as shown in the results.

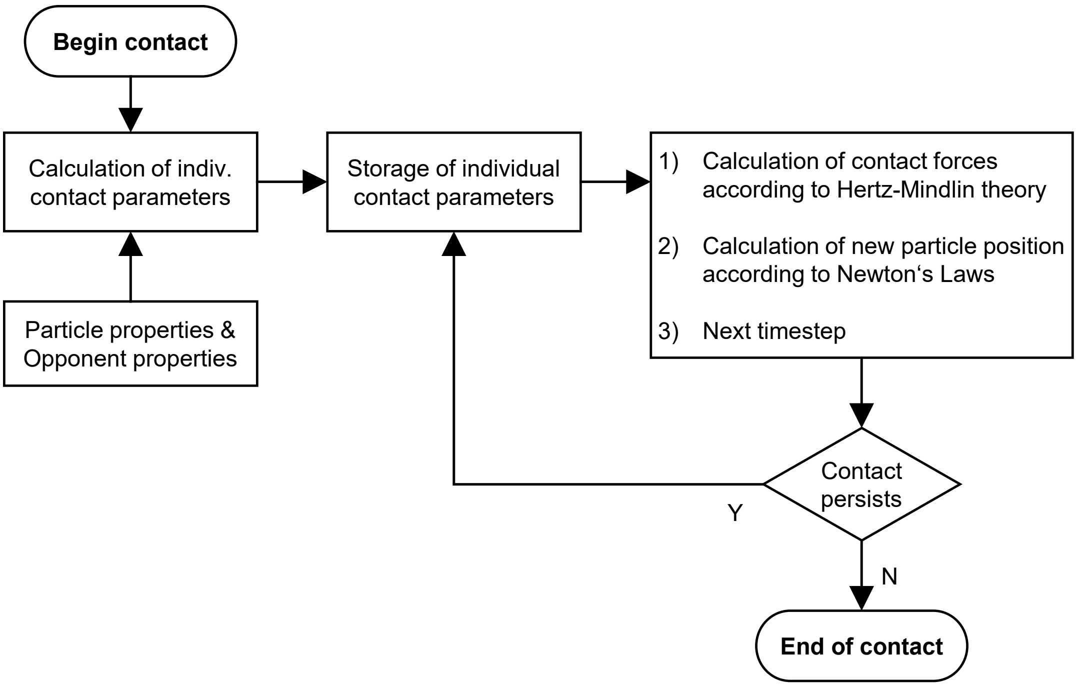
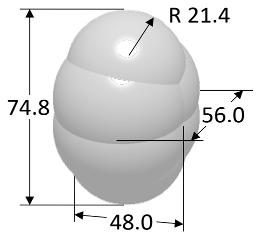


Figure 3: Flow chart of adaptable contact model in the environment of DEM Software EDEM

Each parameter required for the viscoelastic model was investigated using specified experiments. Potatoes of the Belana variety were examined under controlled environmental conditions. Belana variety was chosen due to their typical potato shape and properties. To minimise premature damage and retain the harvesting-like conditions, the potato tubers were harvested manually. The properties are sorted according to their square mesh diameter (SMD) to reduce deviations induced by tuber size (Table 1). The associated susceptibility to impact damage assumed to increase with dimensions. Therefore a target size of SMD 50 to SMD 55 was chosen for the modelling, being in the upper range of the size distribution of this variety, in order to increase the model adequacy in harvest simulations. The number of repetition (n) of each experiment is given next to the measured values. The density was determined by utilising the Archimedes' principle. The tip radius of curvature was measured with a dial indicator in two planes with 90° offset to get a mean value similar to van Zeebroeck et al. (2007). YM and Poisson's ratio were measured with potato samples cut to a known geometry and pinched on a universal testing machine. The COR was determined with a pendulum test comparable to that presented by Bajema et al. (1998 b). The COR was measured for different effective drop heights h_{eff}, with the highest COR for h_{eff} = 20 mm and the lowest COR for h_{eff} = 500 mm. The coefficient of rolling friction was the only parameter determined by a simulative approximation method. The measured parameters were averaged to develop an idealised tuber model represented by six spheres as shown in Table 1.

Table 1: Potato tuber material properties, measurements and idealised model

Potato tuber material properties	Experiment results Belana 2018 (n)	Idealised simulation model	
Square mesh diameter in mm	50 to 55	50 to 55	
Mean tuber weight in g ($\mu_m \pm \sigma_m$)	120.8 ± 14.0 (116)	119.9 ± 30.0	
Mean density ρm kg/m^3	1.07 ± 0.02 (30)	1.08	
Mean length in mm ($\mu_l \pm \sigma_l$)	75.3 ± 5.9 (116)	74.8 +5.8/-6.8	
Mean tip radius in mm ($\mu_r \pm \sigma_r$)	21.8 ± 2.5 (24)	21.4 +1.7/-2.0	
Coeff. of static friction μ_S (steel w. sand)	0.3 - 0.5 (10)	0.38-0.475	
Young's modulus E in MPa	2.4 - 7.2 (5)	2.7 - 5.7	
Poisson ratio ν (5-15% strain)	0.42 ± 0.07 (5)	0.41	
Coeff. of restitution e (500 mm - 20 mm)	0.53 - 0.69 (12)	0.56 - 0.66	(Potato tuber particle consisting six spheres, values in mm)
Coeff. of rolling resistance c_{RR} (steel)	-	0.055	



The main difference between the measured values and the idealised model is the standard deviation σ_m of the mean tuber weight μ_m. The potato tubers used to measure the properties were solely in the SMD 50 to SMD 55 size range whereas the potato tubers later used in the validation experiments were in the SMD 40 to SMD 60 size range. To accommodate this wider range of size the idealised model uses a higher standard deviation of the mean weight. This causes the standard deviations of the tuber length σ_l, and tip radius σ_r, according to Equation 1:

$$\sigma_{l,r} = \mu_{l,r} \cdot \left(\sqrt[3]{1 \pm \frac{\sigma_m}{\mu_m}} - 1 \right) \qquad \text{(Eq. 1)}$$

Validation rig for potato tuber simulation model

The tuber model needs to reproduce the tuber flow and impact behaviour in order to be used in harvesting process optimisation. The validation of the impact behaviour verifies the predetermined parameters YM, Poisson's ratio and COR, whereas the validation of the material flow verifies density, shape, rolling resistance and friction. Figure 4 shows the main influencing properties on the target characteristics.

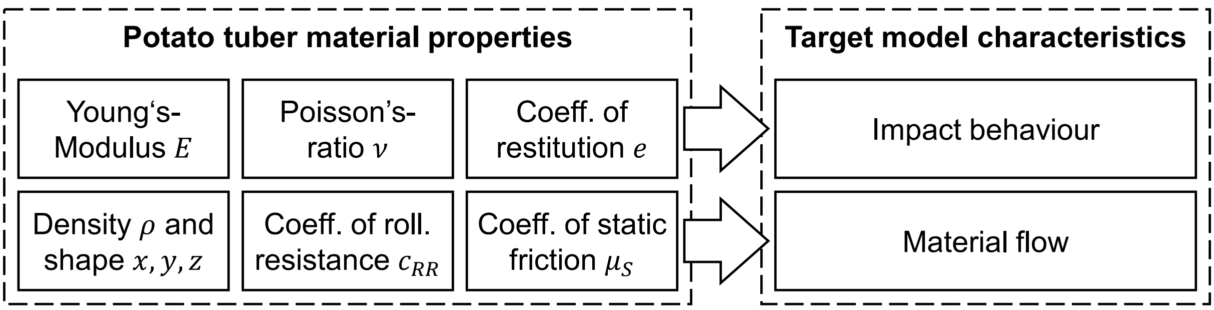


Figure 4: Parameter of potato particle model and target model characteristics

Figure 5 (a) shows the concept of the validation test rig with the main elements, being a conveyor belt and an impact plate. Material flows in potato harvesting machines are usually realised via conveyor belts.

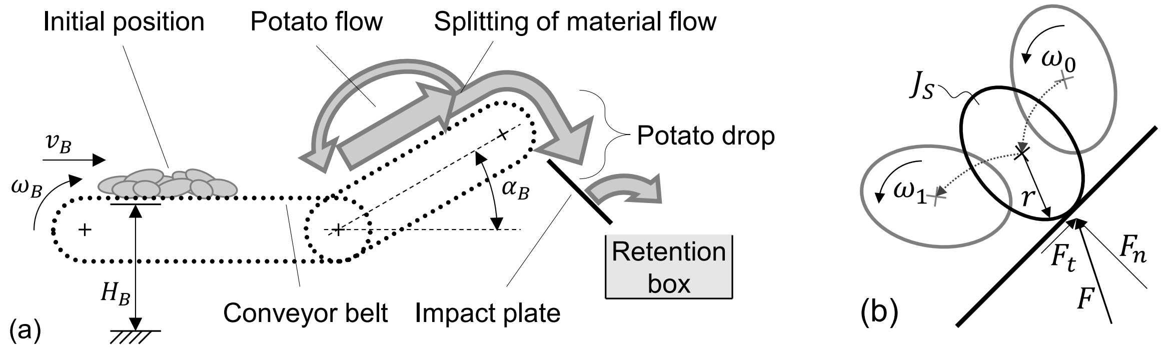


Figure 5: Concept of the validation rig and process (a) with a detailed view (b) on the impact of potato tubers and the angular velocity

Splitting the discontinuous material flow by an inclined conveyor head enables the measurement value 'relative throughput' T_{rel} as proportion of the amount of dropped potato tubers $m_{retention}$ to the initial potato tuber amount $m_{initial}$ (Equation 2).

$$T_{rel} = \frac{m_{retention}}{m_{initial}} \cdot 100\% \qquad \text{(Eq. 2)}$$

The impact behaviour of potato tubers can be observed through the ones, dropping on the impact plate. Generally, the impact force is consulted to evaluate impact behaviour (Diels et al. 2016, Winkelmann et al. 2000). The measurement of force on large areas combined with short impact time is quite challenging and in this case avoidable. The inclination of the impact plate of 45° causes the potato tubers to rotate after impact as described in Figure 5 (b). According to Newton's laws of rotational motion (Equation 3), the angular acceleration depends on the torques M_i and excentral forces F_i with their lever arm a_i subjecting the roatational intertia J_S. Since the the angular velocity ω is the integral of the angular acceleration (Equation 4), it also depends on the applied force. This gives evidence that the angular velocity can be used to assess the impact behaviour.

$$\ddot{\varphi} = \frac{\sum M_i + \sum F_j \cdot a_j}{J_S} \qquad \text{(Eq. 3)}$$

$$\omega = \int \ddot{\varphi}\, dt \qquad \text{(Eq. 4)}$$

In the experiment, the angular velocity after impact ω_1 can be measured via high-speed video camera. The field of view of the camera is positioned lateral to the impact plate to ensure that the optical axis is parallel to the main rotational axis of the impacting potato tubers. The angular velocity is measured manually with the time of the tubers to complete a half or full rotation after impact. For each validation test, 10 randomly picked tubers are measured.

Conveyor belts differ in material, rod spacing and rod style according to their specific task. The selected belt for the validation test rig consists of stiff steel rods and a small spacing of 27.85 mm, which is usually used in potato picking applications. To alter the material flow and impact behaviour, the belt speed v_B and the conveyor head angle α_B can be changed from v_B = 20 m/min to 60 m/min and α_B = 20.0° to 27.5°. To increase drop height and alter the impact behaviour the base of the validation test rig can be raised from a low position of H_B = 1050 mm = "L" to a high position H_B =1170 mm = "H".

Table 2 gives an overview of the validation experiments carried out. In six main settings for belt speed and conveyor head angle, two to five different potato sets were investigated. The potato sets differ in total number and average weight of the tubers, and have a total weight of approx. 20 kg in common. Each potato set used three to five times to limit accumulated damage resulting in 8 to 30 measurements per setting. At the beginning of each test, the tubers were compactly placed on the conveyor belt. The tuber amount in the retention box is measured after each test. The angular velocity after impact is measured for ten tubers in each test, generating about 80 to 300 measurements per setting. Histograms of each setting provide the mean angular velocity with the standard deviation for the tubers after the impact.

Table 2: Validation setup

Belt speed in m/min	Conveyor head angle in °	Total tuber number (average tuber mass in g, n.m. not measured)	Number of repetitions per set	Base height of conveyor (L = 1050 mm H = 1170 mm)
20	20.0	136 (n.m.), 145 (n.m.), 158 (126.2), 123 (163.4), 165 (121.2)	5, 5, 5, 3, 5	L, L, H, H, H
	22.5	130 (153.8), 161 (124.2), 138 (144.9)	5, 5, 3	H, H, H
60	20.0	126 (140.3), 139 (138.8), 138 (155.1), 121 (165.3), 141 (141.8)	5 (each set)	L, L, L, H, H
	22.5	127 (158.3), 138 (145.1), 119 (168.1), 130 (153.8), 136 (147.4), 140 (142.9)	5 (each set)	L, L, L, H, H, H
	25.0	167 (119.8), 138 (144.9)	5, 3	H, H
	27.5	167 (119.8), 161 (124.2)	5, 5	H, H

The simulation model is a full-scale representation of the validation test rig as shown in Figure 6. The simulations are conducted for each setting and each set of potatoes by scaling the average tuber mass according to Table 1 and Table 2. The 'relative throughput' can be metered via control geometries for each calculation cycle. The particle rotation can be determined through histograms evaluating the angular velocity ω_Y of all particles dropping on the impact plate. The resulting mean angular velocity of each setting compares to the experimental values for validation.

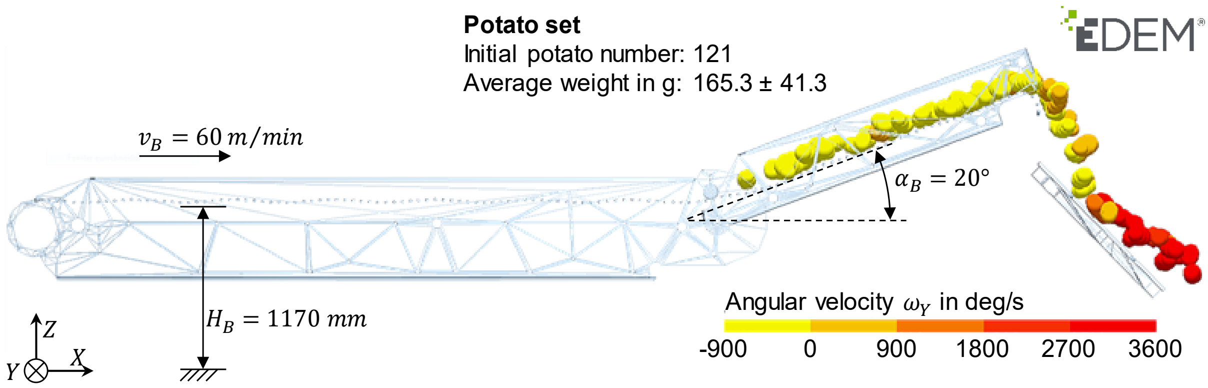


Figure 6: Lateral view of the simulation model with particle colored based on the angular velocity in Y-axis

Results of the validation process

The average 'relative throughput' in experiment and simulation can be seen in Figure 7. The base height of the belt has no effect on the 'relative throughput' and therefore the displayed results include both heights. For the lower conveyor head angle up to α_B = 22.5° experiment and simulation results are very close. With increasing conveyor head angle the deviation between experiment and simulation increases a bit. The 'relative throughput' in the experiments increases with belt speed and decreases with conveyor head angle. The simulation model provides qualitatively the same correlations and for small conveyor head angle even quantitatively correct results. This verifies the model ability to reproduce a correct material flow.

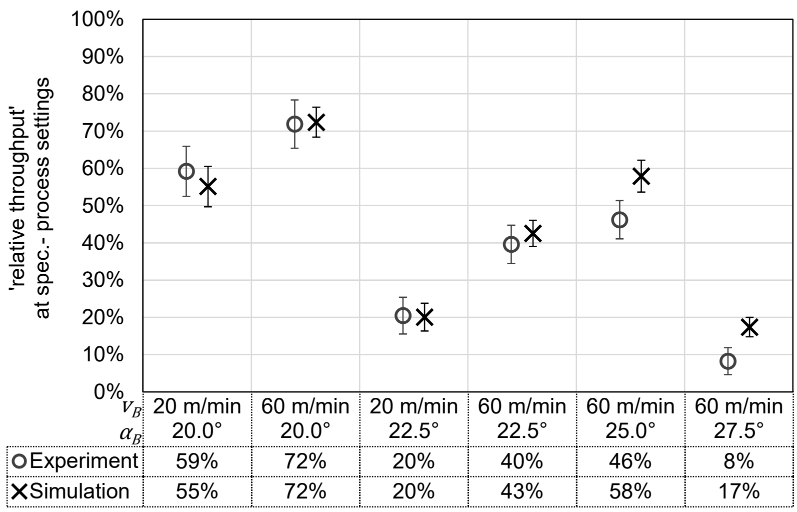


Figure 7: Comparison of 'relative throughput' between simulation and experiment

The measurement of angular velocity after impact in experiment was only possible if a considerable amount of potato tubers were dropped over the impact plate. Therefore, the settings with high inclination angle were excluded from the validation. In order to measure the effect of an increased drop height the settings with a belt speed of v_B = 20 m/min and inclination angle of α_B = 20° were investigated. To analyse the effect of belt speed on the particle rotation, the settings at inclination angle of α_B = 20° at base height of H_B = 1050 mm were used. The combination of both effects was tested at a belt speed of v_B = 60 m/min, an inclination angle of α_B = 20° and a base height of H_B = 1170 mm. Figure 8 shows the distribution of angular velocity of potato tubers after impact for simulation and experiment. These results were taken at a specific setting and for a single potato set but with five repetitions for the experiment. Since in simulation the rotation of all tubers could be measured, a single simulation run for each potato set at each setting was analysed. Performing several simulations with same settings and random particle generation have shown marginal difference in potato rotation.

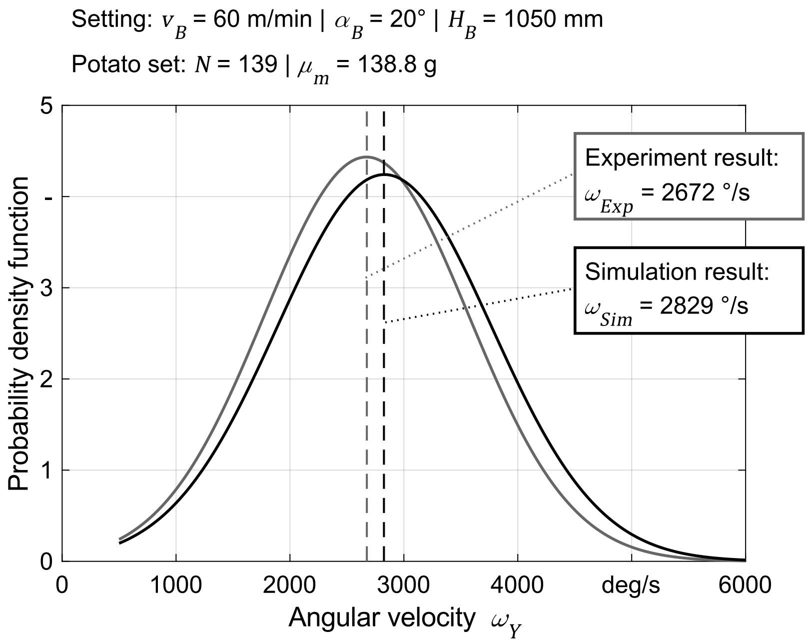


Figure 8: Distribution of angular velocity of potato tubers after impact for simulation and experiment

The results of angular velocity of potato tubers for experiment and simulation are displayed in Figure 9. The deviation in angular velocity between experiment and simulation is more significant than the deviation in the 'relative throughput'. The low sensitivity of angular velocity on investigated test settings and the high standard deviation in each setting indicates that other factors like size, shape or impact area have an effect on angular velocity. Neglecting the effect of different settings, the simulation model is able to reproduce the mean values and standard deviation for potato tuber rotation after impact and shows approximatly the same sensitivity on the investigated test settings. The simulation model provides quantitatively accurate results for tuber rotation, hence the impact behaviour is considered acceptable.

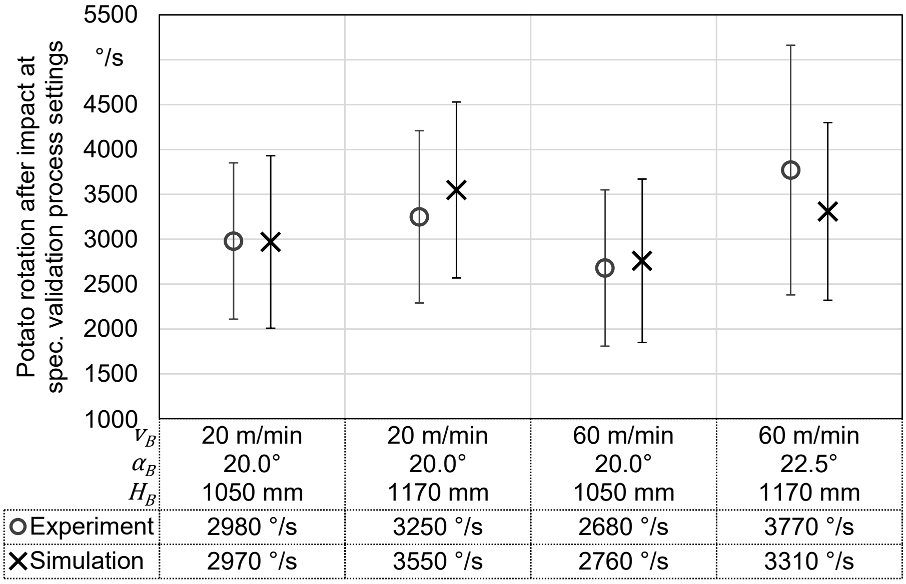


Figure 9: Comparison simulation and experiment of potato tuber angular velocity after impact

Conclusions

The research shows that the essential model behaviour of potato tuber can be validated on a single test rig. Therefore, all target model characteristics have to be considered in the development of the validation process. The results demonstrate the models' ability to correctly reproduce material flow and impact behaviour of harvesting-like processes. The model solely consists of potato particles and rigid material elements. In order to benefit of the full potential of the DEM simulation, further contact behaviour for interaction with earth clods, potato plants, stones as well as deformable machine parts for example pintle belts should be modelled and added. Therefore, further research is planned in order to implement flexible geometry elements and constituent materials of the potato harvest material flow.

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