DEM Simulation for the Predicted Model of Total Rice Seeds Mass in a Vibratory Conveyor

Pirapat Arunyanart and Supattarachai Sudsawat*

***Abstract*—This research aims to achieve the maximum total rice mass output for the vibratory conveyor by selecting the suitable machine parameters. The techniques that were implemented to maximize the total rice mass output are the Design of Experiment (DOE) and the Response Surface Methodology (RSM) based on the Discrete Element Method (DEM). The driving frequency, vibrating amplitude, and vibration angle were shown as significant parameters and the optimal exact methodology was employed to seek these suitable values by DEM simulation test. Analysis of Variance (ANOVA) was used to validate experiments. This research outcome can be a good guide method for the vibratory conveyor design by implementing DEM simulation along with DOE and RSM.**

***Index Terms*—The vibratory conveyor, Design of Experiment (DOE), Response Surface Methodology (RSM), the Discrete Element Method (DEM)**

I. Introduction

The vibratory conveyor is one of the industrial applications in many clusters that usually combine to be a part of processes such as the usage of sieving, feeding, mixing, and so on. The reasons why the vibratory conveyor has been applied to various processes are the relatively simple design and the low energy consumption [1]. For vibratory conveying design, many constraints which have been concerned to avoid for particle handling are a harmonic phenomenon [2], an unstable bulk material handling, a failure of vibration machine, an overload of driving power, and a reduction of the volumetric flow rate [1]. Therefore, the vibratory conveying machine requires indicator guideline and seek for the optimal constraint values of a perfect bulk materials handling. One of the various methodologies for proving the design parameters of conveyor machines is the Discrete Element Method (DEM). This method was originally presented by Cundall and Strick [3] that has been widely implemented to solve bulk material handling systems [4]. DEM is a computational technique that becomes an effective method to evaluate the dynamic motion of bulk materials in a mechanical system, to optimize the crop processing machines, and so forth [5]. For DEM simulation of bulk materials handling on vibrating conveyors, many researchers have applied DEM methodology to seek a solution for machines. For instance, Andre applied the DEM method to indicate the bulk solid reaction on vibratory conveyors. This research work provides a guide of throw number for the bulk materials handling behavior at least equal to 2 and illustrates that DEM-simulation is an efficient method for solving vibratory conveyor design [1]. Simsek *et al.* [6] investigated bulk material dispersion during vibrating conveyors through the DEM simulation method. The results concluded that the particle sizes were affected by the dispersion of material handling. Some vibratory conveyor researchers had validated parameter designs that impacted materials handling via DEM simulation investigation. For example, there was a dynamic analysis of the vibratory feeder at various frequencies. It had been used DEM simulation for validating the motion of vibratory machine parts under different loads for vibratory feeder design [7]. Another research employed zigzag morphology to design vibratory plate conveyors by simulating material handling behavior through the DEM method. The result provided that the zigzag morphology for the vibratory conveyor was used for a low gravity environment on the lunar surface [8]. Moreover, there was an implementation of DEM methodology to indicate a two-way changeable vibratory conveyor [9]. The outcome present that this vibratory conveyor can illustrate new solutions of safety and functionality for conveying design and can avoid resonance frequencies based on DEM simulation support. Many researches concentrated on vibratory conveyor parameters such as amplitude, frequency, and inclination angle of vibrating machine for solving materials handling [10 –12]. Fan *et al.* [10] and Zurovec *et al.* [11] applied DEM simulation for analyzing and solving the dynamic properties of separating coated fuel and steel grit particles by considering amplitude, frequency, and inclination angle of vibration separator. The result shows the optimal values for the vibration separator design of each bulk material. In this research work, rice particles will investigate for vibratory conveyor design. Some former researchers studied vibrating machine designs for rice seeds [13, 14]. There were attempts to seek for the suitable parameters that match rice seed handling.

As literature review researches, they have not found any vibratory conveyor researches on the optimal equation model for seeking suitable machine parameter for vibratory conveyor. Therefore, the objectives of this paper are the indication of a polynomial equation model of machine parameters for vibratory conveyors through DEM simulation experiments and to illustrate the optimal values of parameters that can deliver the maximum total mass flow rate of rice seeds.

II. Materials and Method

Hertz-Mindlin (no slip) contact model for rice particles was employed in DEM simulation [15]. The model consists

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of both elastic and damping components as both normal and tangential forces. The equation of the contact forces in the normal direction (F_n) as in Eq. (1).

$$F_n = \frac{4}{3}E^*\sqrt{R^*}\sqrt{\delta_n^3} + C_n\sqrt[4]{\delta_n}v_{r/n} \quad (1)$$

$$\text{Given } E^* = \left(\frac{1-v_i^2}{E_i} + \frac{1-v_j^2}{E_j}\right) \text{ and } R^* = \frac{R_iR_j}{R_i + R_j}$$

where E^* is the equivalent Young's modulus, R^* is the equivalent radius, δ_n is the normal overlap, and $v_{r/n}$ is the normal relative velocity between rice grains; the equation for the normal damping coefficient C_n presented as in Eq. (2).

$$C_n = -2\sqrt{\frac{5}{6}}\frac{\ln e}{\sqrt{\ln^2 e + \pi^2}}\left(2m^*E^*\sqrt{R^*}\right)^{\frac{1}{2}} \quad (2)$$

whereas the tangential contact force F_t consisted of the stiffness component $F_{k,t}$ and the damping component $F_{d,t}$ and the limited tangential force should under the static friction force as in Eq. (3).

$$F_t = F_{k,t} + F_{d,t} = 8G^*\sqrt{R^*\delta_n\delta_t} + C_t\sqrt[4]{\delta_n v_{r/t}} \quad (3)$$

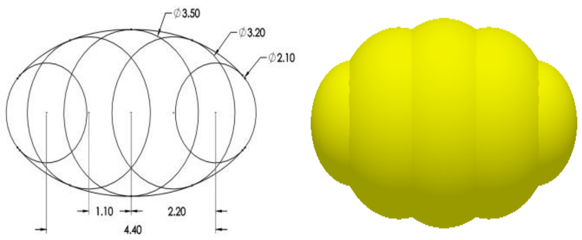
$$\text{Given } G^* = \left(\frac{1}{\frac{2-v_i}{G_i} + \frac{2-v_j}{G_j}}\right)$$

$$\text{and } C_t = -2\sqrt{\frac{5}{6}}\frac{\ln e}{\sqrt{\ln^2 e + \pi^2}}\left(8m^*G^*\sqrt{R^*}\right)^{\frac{1}{2}}$$

where G^* and C_t are the equivalent shear modulus and the tangential damping coefficient, respectively; i and j represent two rice grains. Meanwhile, the dynamic friction in DEM simulation was derived by the torque on the contact surface as shown in Eq. (4).

$$\tau_i = \mu_r F_n R_i \omega_i \quad (4)$$

where μ_r is the dynamic friction coefficient between contacting materials and ω is the relative angular velocity of the rice grain, i is the unit vector. The virtual dimensions of rice seeds as shown in Fig. 1(a) [15]. The rice grain DEM model was created by using a five-sphere combination method as indicated in Fig. 1(b) produced by EDEM software (DEM Solutions Ltd., Edinburgh, UK).



(a) (b)

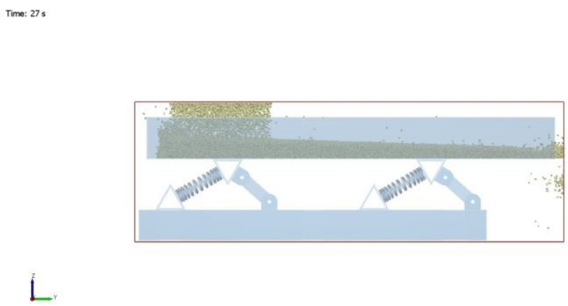
Fig. 1. Rice grain model for DEM simulation. (a) Rice grain dimension parameters, the rice grain consisted of three spherical sizes with 2.1 mm, 3.2 mm, and 3.5 mm diameter, and the grain length is 6.5 mm. (b) Rice grain DEM model.

The material properties of the established model are shown in Table I based on the references from material parameter properties of former researchers.

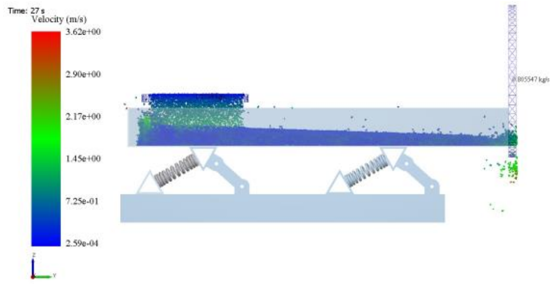
TABLE I: DEM MICRO MATERIAL PROPERTIES OF RICE GRAIN AND STEEL PLATE FROM LITERATURES

Material type	Parameters	Values	Sources
	Material Properties		
Rice grain	Poisson's ratio	0.28	[16]
	Solid density (kg m^3)	1350	[16]
	Elastic modulus (GPa)	0.375	[16]
Steel	Poisson's ratio	0.3	[17]
	Solid density (kg m^3)	7800	[17]
	Elastic modulus (GPa)	206	[17]
Interaction parameters			
Coefficient of static friction	Rice grain-rice grain	0.425	[18]
	Rice grain-Steel	0.58	[17]
Coefficient of dynamic friction	Rice grain-rice grain	0.01	[18]
	Rice grain-Steel	0.01	[17]
Coefficient of restitution	Rice grain-rice grain	0.5	[18]
	Rice grain-Steel	0.5	[17]

For the vibratory conveyor design, the model dimension is shown in Fig. 2 (a) whereas Fig. 2 (b) illustrates the results of rice seed handling through DEM simulation.



(a)



(b)

Fig. 2. (a) Model of the vibration conveyor and (b) DEM simulation for rice seed handling through the vibration conveyor.

The methodology was comprised of identifying micro parameters from the literature, Plackkett-Burmann screening efficient parameters for DEM vibratory simulation, designing the experiments through Box-Behnken design array, creating total mass output model through a quadratic equation model, searching the optimal parameters of vibratory conveyor machine and gaining the total rice mass transportation via the optimal values. The process can be illustrated in Fig. 3.

The ranges of suitable machine parameters were selected according to the concept of a characteristic factor for the handling behavior called a throw number that should be more than 2 [1]. The machine parameter range was illustrated based on two levels as indicated in Table II.

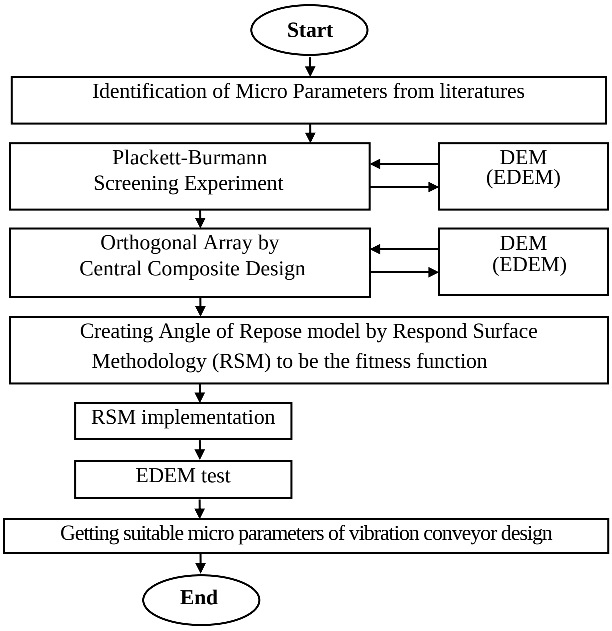


Fig. 3. Flow chart of research experiments.

TABLE II: PARAMETERS AND LEVELS FOR THE VIBRATION CONVEYOR DESIGN

Screening Experiment (Unit)	Symbol	Level	
		Low	High
1.Driving frequency (Hz)	A	11	17
2. Amplitude (mm)	B	15	50
3. Vibration angle (°)	C	30	50

The parameter screening process was used to evaluate main and interaction effects. The 3-factor of the Plackett-Burmann Method (PB) with two levels each as indicated in Table III. All the design experiments were simulated through EDEM software to indicate the total mass output of rice seeds. The total mass output results were then considered for indicating influent vibrating parameters through analysis of the variance.

TABLE III: PLACKETT-BURMANN SCREENING EXPERIMENTS THROUGH EDEM SIMULATION SOFTWARE

No.	Factors			Total mass output (kg)
	A	B	C	
1	11	15	30	910.34
2	17	50	30	822.66
3	17	50	50	1079.05
4	11	15	30	912.57
5	11	15	50	1041.44
6	17	15	50	1015.58
7	11	50	30	1567.56
8	17	15	30	880.45
9	11	50	50	1567.56
10	17	50	30	849.76
11	17	15	50	1015.04
12	11	50	50	1567.56

After the screening, the significant parameters could be contributed and used in the Response Surface Method (RSM) as indicated in Table IV.

TABLE IV: BOX-BEHNKEN DESIGN FOR VIBRATION CONVEYOR

Symbol	Level				
	–α	–1	0	1	A
A	11	11	14	17	17
B	15	15	32.5	50	50
C	30	30	40	50	50

In this stage, Box-Behnken Design (BB) was assigned to design and run the experiments. Before creating the total mass quadratic model, BB had to be created a designed array and also the total rice mass results from EDEM software as illustrated in Table V.

TABLE V: DESIGN AND RESULTS OF BOX-BEHNKEN DESIGN EXPERIMENTS

Run Order	Factors			Total mass output (kg)
	A	B	C	
1	17	15	40	789.97
2	14	32.5	40	1221.76
3	11	32.5	50	1251.94
4	11	15	40	843.44
5	11	32.5	30	1028.85
6	14	15	50	935.37
7	14	32.5	40	1221.76
8	17	32.5	50	764.37
9	14	50	50	1595.82
10	17	50	40	672.42
11	14	50	30	1344.23
12	17	32.5	30	640.43
13	11	50	40	1430.00
14	14	15	30	806.69
15	14	32.5	40	1221.76

After creating BB array experiments, the quadratic equation had been constructed based on the DEM simulation of total rice mass results as illustrated in Eq. (5).

$$Y = A_0 + \sum_{i=1}^{k} A_i X_i + \sum_{i<j}^{k} A_{ij} X_i X_j + \sum_{i=1}^{k} A_{ii} X_i^2 \quad (5)$$

where Y is the total mass output, A_0 is the constant value, k is the number of design variables, A_i are linear coefficients, X_i are the independent factors, A_{ij} are the coefficients of the cross-product value, and A_{ii} are the coefficients of quadratic values. The objective function through RSM methodology, the total mass model was assigned to seek the suitable machine parameters based on DEM simulation tests as indicated in Eqs. (6) and (7) respectively.

$$\text{Find} \quad \mathrm{X} = [\mathrm{A}, \mathrm{B}, \mathrm{C}] \quad (6)$$

$$\text{Maximum} \quad \mathrm{Y(X)} \quad (7)$$

Subject to: $11 \le \mathrm{A} \le 17$ (Hz)

$15 \le \mathrm{B} \le 50$ (mm)

$30 \le \mathrm{C} \le 50$ (°)

Other micro material parameters were employed as indicated in Table I.

III. Results and Discussion

After DEM input machine parameters and their two levels (low, and high levels) were set in Table II. The PB method was established for total mass output as 12 conditions using EDEM simulation with an actual duration of 27 s shown in Table III. The total mass output resulting from the DEM simulation was investigated as the dependent response whereby the total mass output values had a range from 880.45 kg to 1595.82 kg as shown in Table III. Table VI indicated a conclusion of the results from the PB method. The main contribution that affects the total mass output were the driving frequency, vibrating amplitude, and vibration angle respectively. The total percentage that was contributed from these three operating factors was more than 85%.

TABLE VI: DEM Parameters from the Plackett-Burmann Design of Experiment Listed in Order according to Their Percentage Contribution

Symbol	Effect	Mean Square	Percent Contribution (%)	Contribution Order
A	−499.8	749497	40	1
B	462.2	640907	34	2
C	368.6	407613	25	3

After providing the three main factors from the initial screening step, the BB method was simulated to suggest the total mass output as shown in Table V. Then an Analysis of Variance (ANOVA) was employed to validate and seek the predicted total mass output model of vibratory conveyor simulation through a backward elimination procedure as illustrated in Table VII. The ANOVA significant factors that show effects were "df", "Adj SS", "Adj Ms", "F-Value", and "P-Value". "df" is a degree of freedom. "Adj SS" is the adjusted sum of squares. "Adj Ms" is adjusted mean squares, "F-Value" is a ratio of variation between sample means and variation within the samples and "P-Value" is a probability that shows the inspected results as less than 0.05. In Table VII, there is the presentation of the probability ratio ("P-Value") for main effects, a square term, and an interaction term that is less than 0.05. Therefore, this table indicated a backward elimination situation that the driving frequency, vibrating amplitude, and vibration angle mainly affected the total rice mass output. There were also square impacts of A and interaction impacts between A and B factors. Following response surface methodology could provide a polynomial total mass output equation (TOP) of the main three factors as established in Eq. (8).

$$\text{TOP (kg)} = -5867 + (864 \times \text{A}) + (58848 \times \text{B}) + (9.09 \times \text{C}) - (29.42 \times \text{A}^2) - (3353 \times \text{A} \times \text{B}) \quad (8)$$

Substituting Eq. (8) added into an objective function Eq. (7), the driving frequency, vibrating amplitude, and vibration angle were obtained as the optimal values. Then the optimal values of the driving frequency, vibrating amplitude, and vibration angle were provided at 11.79 Hz, 50 mm, and 50° respectively giving a DEM simulation result of the total rice mass output as 1,633 kg based on 27 s of actual simulation times.

TABLE VII: ANOVA Table for Total Mass Output Model (after Backward Elimination)

Source	df	Adj SS	Adj MS	F	P
Model	5	1154975	230995	26.61	0.000
Linear	3	769242	256414	29.53	0.000
A	1	355763	355763	40.98	0.000
B	1	347357	347357	40.01	0.000
C	1	66121	66121	7.62	0.022
Square	1	261790	261790	30.15	0.000
A*A	1	261790	261790	30.15	0.000
Interaction	1	123943	123943	14.28	0.004
A*B	1	123943	123943	14.28	0.004
Error	9	78139	8682		
Lack-of-Fit	7	78139	11163		
Pure Error	2	0	0		

Addition: S = 93.17, R-Sq = 93.66%, R-Sq (adjust) = 90.14%.

IV. Conclusion

This research, using DEM simulation for seeking suitable machine parameters for vibratory conveyors, can summarize as follows:

1. Plackett-Burmannn design of experiment, repose surface methodology as Box-Behnken design type, and optimal exact methodology (Actual total rice mass output = 1,633 kg) were used to seek machine parameters of vibratory conveyor through DEM simulation then the driving frequency, vibrating amplitude, and vibration angle were found to strongly influence the total rice mass output.
2. A predicted quadratic polynomial equation clearly explained the relationship between the total mass flow and the three sensitive DEM machine parameters.
3. This research can be a guide method for vibratory conveyor design by using DEM simulation combined with the design of the experiment method.
4. Further work, the validation of the calibrated DEM parameters of the vibratory conveyor should be applied to the actual vibratory machine for running and testing research for other bulk materials.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

S. Sudsawat conducted the data compilation, set the research methodology and reviewed and wrote the final version of the research paper; P. Arunyanart conducted the literature review and helped write the draft version of the research; all authors had approved the final version.

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