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MODELLING OF QUALITY CHANGES IN A MULTICOMPONENT GRANULAR MIXTURE DURING MIXING

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ABSTRACT

The paper presents results of modelling of quality changes in a muliticomponent non-homogenous granular mixture during mixing in an industrial worm mixer. The analysis was carried out for three granular mixtures: nine-component, ten-component and twelve-component. Modelling was performed with the use of nonlinear regression. Dependent variable was a residual sum of squares (mixture quality parameter), whereas independent variables were: number of components and mixing time. Two-dimensional dependence was constituted by square function formula. The aim of the study was to describe quality changes of muliticomponent, non-homogenous granular mixtures (nine, ten and twelve – component) during mixing in a vertical mixer with worm agitator, with the use of nonlinear regression model. Atypical aspect of the mixing process was a specific recirculation of the mixed components with the use of bucket conveyor during the process.

Key words: granular materials, granular mixture, muliticomponent granular mixture, residual sum of squares, nonlinear regression

INTRODUCTION

Mixing process course, that is its development in time, is one of more important issues related to theory and practice of technologies concerning obtaining mixtures of possibly homogenous composition [3]. Due to its complexity, the mixing process is difficult to describe with the use of simple analytical methods. Depending on mixing methods and types of mixed components, the course of this process may possess qualities of various models.

In agricultural and food practice the use of „artificial intelligence" as a tool for modelling may be encountered increasingly often, it is used among others for modelling of: family agricultural holding's productivity [11], agricultural production process [9] or technical objects operation process [4]. Usefulness of neural networks in describing quality changes of granular systems mixed with the use of normal pour out method and in a static device was described by Tukiendorf [15]. It was proved, that the results of process modelling with the use of reverse propagation method do not differ from the ones estimated by the Markov chain [14]. Interpretation of changes occurring in time, with the use of artificial neural networks is certainly one of the latest methods, which use enables simulation of very complex functions. The issue of modelling of non-homogenous granular systems' mixing process has been the object of the authors' interest for years. In the previous works, the possibility of using artificial neural networks and nonlinear regression in description of quality changes of a granular mixture during mixing was pointed out [5, 10].

Despite the fact, that many research works have been devoted to this field, mixing of granular materials is a current issue. It is a complex process dependent on many parameters such as: characteristics of mixed materials, mixing device type, process conditions. Many research carried out in laboratory conditions explain partial mechanisms which govern the mixing. The majority of real granular mixtures, which can be encountered in industry, e.g. in feed mixing plants, are constituted by mulitcomponent non-homogenous systems. In particular, mixing processes related to this field have not yet been thoroughly studied. Mulitcomponent system is a system in which the number of solid components amounts to at least 3. At the same time, mixing of k components ($k > 2$) creates problems of a completely new quality [2]. This system may be examined as a two-component system, assessing the mixture's state from the point of view of the A component, and all of the remaining components may be treated as one B component. The majority of real granular mixtures encountered in industrial practice are non-homogenous systems. Description of this mixture's state and kinetics of the process belong to the main problems of mixing [2]. Most research that has been conducted before, concerns mainly two and three-component mixtures. There are only few works describing mixing of mulitcomponent non-homogenous granular systems.

Regression analysis constitutes the most widely and frequently used statistical method of modelling of dependences between variables [1]. Simple model of linear regression may be applied only when dependence between variables is linear. In practice, however, this situation is very uncommon. Analysis of empirical values of variables often inclines to the use of nonlinear regression. Nonlinear regression allows to determine any type of dependence between variables.

Relative measure of adjustment of regression lines to data may be the square of sample correlation coefficient r^2, called coefficient of determination. It is the most common measure of adjustment [12]. The coefficient of determination may be defined as this part of Y variable, which is explained by occurrence of the assumed dependence between X and Y. When r^2 equals 1, variable X explains 100% of variable Y's variance, which means that the observation' results lie exactly on the regression line and errors are zero. When the value of coefficient equals 0, then all deviations from the regression line are due to errors. The paper presents the possibility of nonlinear regression model's use in description of quality changes of mulitcomponent granular mixtures during mixing with the use of a vertical mixer.

AIM OF THE STUDY

The aim of the study was to describe quality changes of mulitcomponent, non-homogenous granular mixtures (nine-component, ten-component and twelve-component) during mixing in a vertical mixer with worm agitator with the use of nonlinear regression model.

RESEARCH METHOD

Experimental research was conducted in industrial conditions in the feed mixing plant Ovigor® in Opole, which is engaged in the production and distribution of feed for pigeons. Production of feeds is composed of several individual operations of technological process, which include the following:

1. charge of individual mixture components with the use of eight-way separators to the appropriate silos,
2. storage of crop seeds in the silos,
3. transport of the selected components with the use of worm conveyors to the belt strain gauge scales,
4. dosage and mass control of individual components by an employee of the mixing plant with the use of control pulpit,
5. charge of mixture components with the use of belt conveyor and vibrating screens to the feed mixer's intake hopper,
6. transport of granular materials from the intake hopper to inside of the mixer with the use of bucket conveyor,
7. mixing in the temporal operation mixer with an immovable chamber and a vertical worm agitator with components recirculation taking place simultaneously (Fig. 1, Tab. 1),
8. packaging of finished products to bags.

In the experimental research the temporal operation mixer with an immovable chamber and a vertical agitator was used. The feed mixer's dimensions have been provided in Table 1 and the schematic drawing have been presented in Figure 1. The mixer's power equals 5.5 kW. Mass of the granular material charged to the mixer equalled:

- 2000 kg in case of a nine-component mixture with the trade name Ovigor® Ekonomik Z – winter,
- 2200 kg in case of a ten-component mixture with the trade name Ovigor® Ekonomik RL – breeding-flight,
- 2099.5 kg in case f a twelve-component mixture with the trade name Ovigor® Ekonomik BP – without wheat.

Fig. 1. Scheme of the feed mixer used to carry out the research – a temporal mixer with immovable chamber and a vertical worm agitator

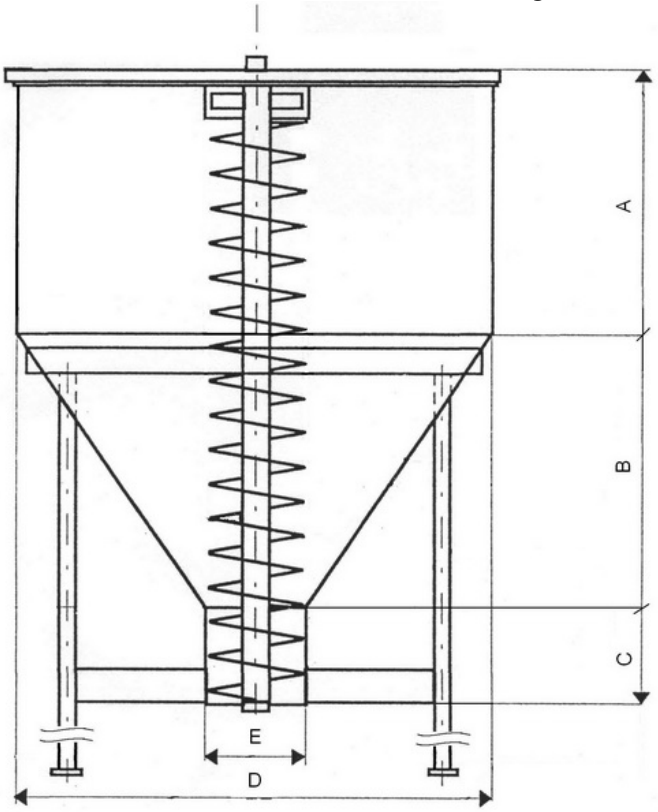


Table 1. Dimensions of the feed mixer (mm) used in the research

Height of the cylindrical part – A	1550 mm
Height of the conic part – B	1600 mm
Height of the pour out outlet – C	300 mm
Inside diameter of the cylindrical part – D	1800 mm
Inside diameter of the pour out outlet – E	300 mm

Composition of granular mixtures, their mass and percentage share, and the mass of components charged to the mixer have been presented in Table 2. Characteristic properties of the mixed materials have been presented in Table 3. Statistical bulk density ρ_n was determined in conformity to the PN-80/C-04532 standard. The average size of seeds was determined with the use of a set of control sieves by means of sieve analysis. Measurement procedure was based on the PN-71/C-04501 standard.

Table 2. Composition of the examined granular mixtures, their percentage and mass share at the charge

Mixture name	Ekonomik Z		Ekonomik RL		Ekonomik BP	
Components of granular mixtures	percentage share, %	mass share, kg	percentage share, %	mass share kg	percentage share, %	mass share, kg
Dari (white sorghum)	1.25	25.00	0.91	20.00	2.86	60.00
Green peas			2.27	50.00	4.76	100.00
Yellow peas	5.00	100.00	6.14	135.00	10.48	220.00
Barley	29.00	580.00				
Kardi (carthamus)					1.19	25.00
Maize	16.00	320.00	36.35	800.00	40.49	850.00
Hulled oat (hull-less)					2.38	50.00
Field pea	10.00	200.00	8.64	190.00	16.20	340.00
Yellow millet	2.25	45.00	6.82	150.00	7.62	160.00
Wheat	30.00	600.00	29.09	640.00		
White rice					1.19	25.00
Black sunflower	1.50	30.00	1.82	40.00	1.88	39.50
Sorghum	5.00	100.00	6.82	150.00	8.57	180.00
Brown vetch			1.14	25.00	2.38	50.00
Total	100.00	2000.00	100.00	2200.00	100.00	2099.5

Table 3. Characteristic properties of the mixed granular materials

Components of granular mixtures	Bulk density kg/m^3	Average size of particles mm
Dari (white sorghum)	723	3.38
Green peas	767	7.24
Yellow peas	771	6.95
Barley	605	3.32
Kardi (carthamus)	500	4.46
Maize	726	8.16
Hulled oat (hull-less)	673	3.22
Field pea	793	6.86
Yellow millet	732	2.26
Wheat	718	3.74
White rice	758	2.25
Black sunflower	430	4.90
Sorghum	697	3.94
Brown vetch	800	4.62

Mixing of the charged granular material was performed by means of movements of the mixer's worm agitator and recirculation of the components with the use of the bucket conveyor. The charged granular material was poured out at the bottom outlet, and next directed to the bucket conveyor, from where it was transported back to the mixer. The components' mixing time amounted to 30 minutes.

Test samples were collected in a discrete way at the mixer's bottom outlet at 30-second intervals. In this way 60 samples were obtained and then analyzed taking into account seed species composition. The tests were conducted in three measurement series. Consecutive samples of the feed mixture were divided into separate components and then the obtained results were analyzed.

STATISTICAL ANALYSIS

Residual sum of squares – mixture quality

As a parameter used in description of the mixture's quality the residual sum of squares was used. Analysis of percentage changes of the components' share in the mixture inclined to searching for a parameter, which would determine with only one universal numerical value the mixture's quality in a certain unit of time. In this way, the quality of granular mixtures were described in the authors' previous articles [6, 7].

In description of the mixing process used for the feed mixture being examined a classical linear regression model was used. Basic equality of variance analysis is the dependence:

$$\sum_{j=1}^{n}\left(y_j-\bar{y}\right)^2=\sum_{j=1}^{n}\left(\hat{y}_j-\bar{y}\right)^2+\sum_{j=1}^{n}\left(y_j-\hat{y}_j\right)^2 \qquad (1)$$

where:

$\sum_{j=1}^{n}\left(y_j-\bar{y}\right)^2$ – the total sum of squares of the response variable's deviations (SST),

$\sum_{j=1}^{n}\left(\hat{y}_j-\bar{y}\right)^2$ – the sum of the Y dependent variable's deviations explained by square regression (SSR),

$\sum_{j=1}^{n}\left(y_j-\hat{y}_j\right)^2$ – the residual sum of squares of the Y response variable's deviations (SSE) [8].

The sum on the right side is the total sum of squares. It is the sum of two components. The first component is the estimated sum of squares, whereas the second component is the residual sum of squares.

In description of the process, one parameter of linear regression was used – the residual sum of squares:

$$SSE=\sum_{i=1}^{n}\left(y_j-\hat{y}_i\right)^2 \qquad (2)$$

where:

y_i – target decomposition of components' frequency,

$\hat{y}_i$ – value predicted from evaluation obtained from simple regression.

The residual sum of squares is a sum of squares of differences between values of the Y variable (target decomposition of frequency of components) and evaluations obtained from simple regression. When the sum of squares equals zero, then all fractions in the particular point of time equal the target (required) values.

Statistical modelling

Modelling was carried out for dependent univariate variable and two independent variables. Dependence between the residual sum of squares, the number of the mixture's components (nine, ten, twelve components) and the mixing time.

$$z = f(x, y) \tag{3}$$

where:

- z – residual sum of squares, dependent variable,
- x – mixing time (s), independent variable,
- y – number of the mixture components (nine, ten and twelve components), independent variable.

It was observed, that dispersion of empirical data reflects dependences of the square function described with the formula:

$$f(x) = ax^2 + bx + c \tag{4}$$

where:

- $a, b, c \in R$ and $a \neq 0$,
- a, b, c – square function coefficients,
- x – variable.

Description of the variables obtained experimentally was made basing on the proposed form: square function:

$$z = ax^2 + bx + cxy + dy^2 + ey + f \tag{5}$$

where:

- z – residual sum of squares,
- x – mixing time, s,
- y – number of the mixture components,
- a, b, c, d, e, f – square regression coefficients.

Evaluation of parameters was carried out in the „nonlinear estimation" module of the program [13]. The regression model was estimated with the use of loss function – sum of squares, defining the method of the smallest squares.

The next step was the choice of estimation method. For the examined case the quasi-Newton method was selected, since it appeared to be a method which allows to find the best estimators. During the next steps, this method evaluates the functions in different points in order to estimate derivatives of the first and second row.

Due to introduction of the parameters' estimation procedure, obtained results were in the form of regression coefficient values of the assumed model, predicted values, value of adjustment of the model to empirical data in the form of the coefficient of determination r^2 and values of residues for each case.
On the basis of the obtained square function formula of specific parameters, modelling of quality changes in an eleven-component granular mixture during mixing was performed.

Statistical modelling results

As a result of statistical modelling, the equation of specific parameters was obtained:

$$z = 0.00007 * x^2 - 0.88x + 0.055xy - 13.29y^2 + 207.67y - 308.31 \tag{6}$$

where:

- z – residual sum of squares,
- x – mixing time, s,
- y – number of components.

The obtained coefficient of determination equals $r^2 = 0.77$

Graphic interpretation of the adjustment of theoretical values to empirical data was presented in the schemes (Fig. 2a, b).

Fig. 2a. Spatial arrangement of the *z* = *f* (*x, y*) dependence (view a)

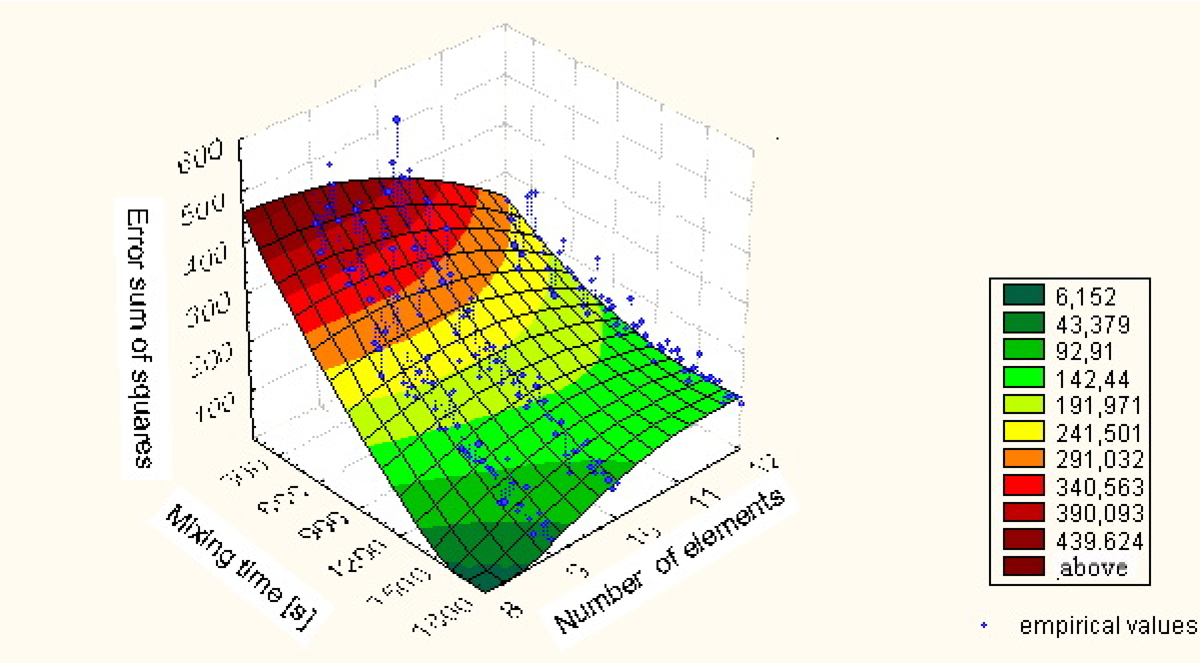
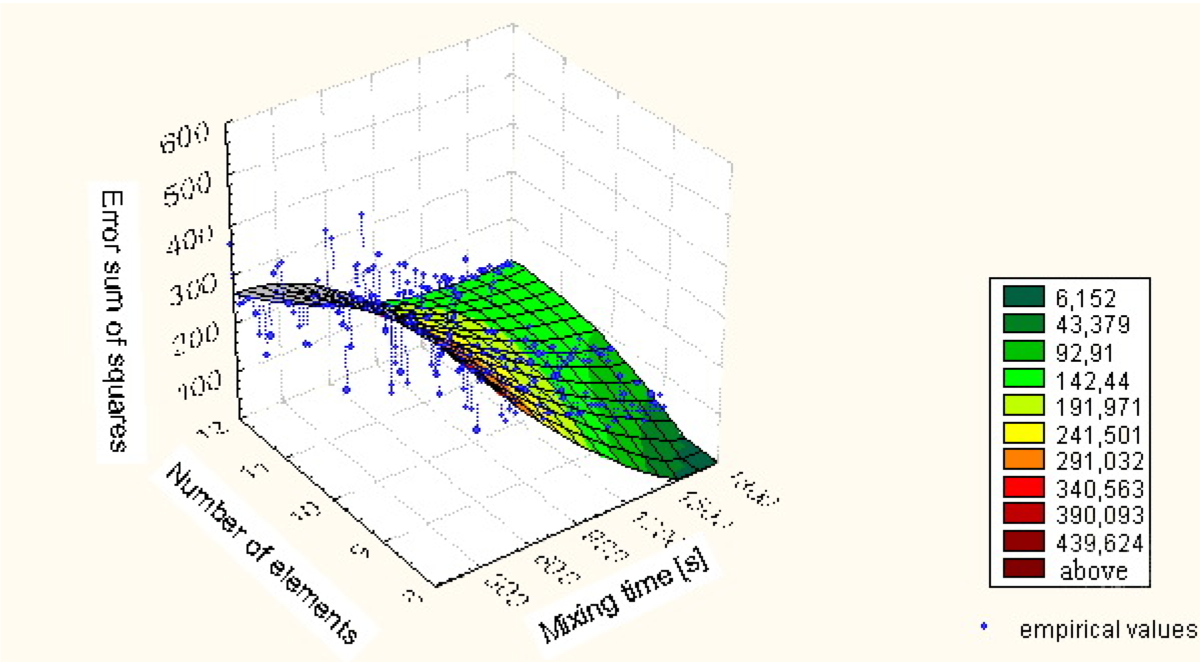
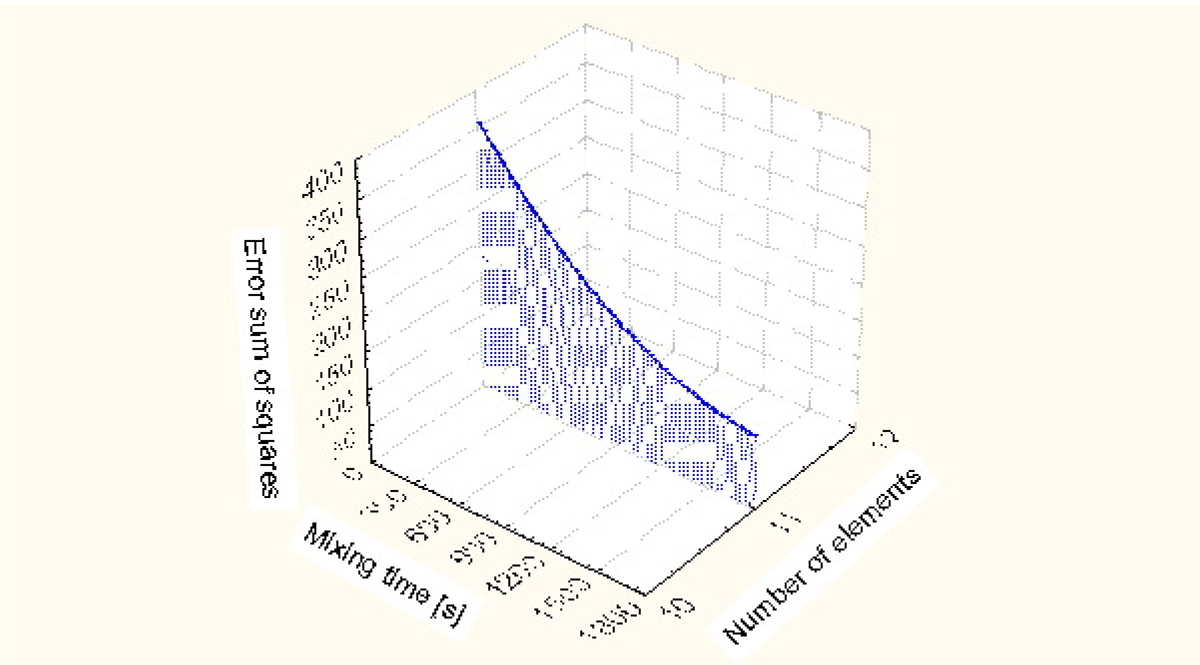


Fig. 2b. Spatial arrangement of the *z* = *f* (*x, y*) dependence (view b)



In the Figure 2a spatial arrangement of the $z = f(x, y)$ dependence obtained as a result of statistical modelling was presented. The values of residual sum of squares, the mixing time expressed in seconds and the number of components of the mixed feeds, were plotted on the axes. The obtained model of linear regression in the form of formula number 6 was presented as the plane enclosed between three axes of the residual sum of squares, the mixing time and the number of components. Additionally, empirical points obtained as a result of experimental research were marked in the scheme. The obtained coefficient of determination which equals $r^2 = 0.77$ shows that the empirical data were quite properly adjusted to the nonlinear regression model. The scheme (Fig. 2a) shows, that with the greater number of components (twelve) the quality of granular mixture is the worst in the last phase of the mixing process. The best mixture quality is obtained for a nine-component mixture, taking into account especially the last stage of the mixing process. The proposed model may constitute a formula for describing quality changes in the muliticomponent granular mixture during mixing in the analyzed mixer for different number of components, even before commencement of the mixing process. The linear regression model (formula no. 6) was used in formulation of the scheme presenting changes of the residual sum of squares' parameter (prediction) during mixing, for eleven components of the mixture (Fig. 3).



This approach is an attempt to find dependence between the number of mixed components and the quality of obtained feed. However, it does not exhaust the issue, in which the mixing process course and method are influenced by many parameters, e.g. diameter and bulk density of seeds.

CONCLUSIONS

1. Linear regression model in the form of the described square function well reflects the quality changes of mixtures in time.
2. It has been observed, that granular systems with the greatest number of components – twelve – have the worst mixing qualities, whereas the best mixture quality was obtained for a mixture with the smallest number of components – nine.
3. The developed regression model enabled prediction of quality changes of a granular mixture in a 30-minute mixing time for an eleven-component mixture, which was not the object of the study.
4. The applied statistical methods – residual sum of squares and non-linear regression constitute appropriate tools for analyzing the mixing process in muliticomponent granular systems.

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