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AN ATTEMPT TO PREDICT QUALITY CHANGES IN A TEN-COMPONENT GRANULAR SYSTEM

Jolanta B. Krolczyk

Original scientific paper
The paper presents an attempt to predict quality changes in a ten-component non-homogeneous granular system during mixing carried out on the mixing line in the following unit: a feed mixer, an intake hopper and a bucket conveyor. The mixing process was conducted with additional external recirculation of the components through the bucket conveyor. The attempt was made based on the knowledge on the course of quality changes in time for the mixture consisting of nine components, eleven components and twelve components. The modelling was conducted in two stages: in the first stage the quality of granular mixtures was determined with the use of the residual sum of squares, in the second stage variables were modelled by means of nonlinear regression. Dependent variable was a residual sum of squares, whereas independent variables were: number of components and mixing time. Two-dimensional dependency was described by square function.

Keywords: *bulk density, modelling, multi-component mixture, vertical mixer*

Pokušaj predviđanja promjena kvalitete u zrnatom sustavu od deset sastojaka

Izvorni znanstveni članak
U radu se opisuje pokušaj predviđanja promjena kvalitete u nehomogenom zrnatom sustavu od deset sastojaka tijekom miješanja na liniji za miješanje uređaja sastavljenog od mješalice hrane, ulaznog lijevka i lopatastog transportera. Postupak miješanja se provodio uz dodatnu vanjsku recirkulaciju sastojaka preko lopatastog transportera. Postupak se temeljio na znanju o promjenama kvalitete tijekom vremena kod mješavine koja se sastojala od devet sastojaka, jedanaest sastojaka i dvanaest sastojaka. Postupak je proveden u dva stadija: u prvom se kvaliteta zrnatih mješavina odredila primjenom preostale sume kvadrata (residual sum of squares), u drugom su varijable modelirane primjenom nelinearne regresije. Zavisna varijabla je bila preostala suma kvadrata, dok su nezavisne varijable bile: broj sastojaka i vrijeme miješanja. Dvodimenzionalna zavisnost je opisana kvadratnom funkcijom.

Ključne riječi: *mješavina s više sastojaka, modeliranje, nasipna težina zrnate materije, vertikalna mješalica*

1 Introduction

The mixing process is a special unitary operation which occurs in a great number of practical applications and in every processing industry [1]. Mixing of particulate solids is an important process on its own, as in blending of the components of a mixed powder; it can also play a critical role in the performance of other particle processing operations such as grinding, granulation, classification and chemical treatment [2]. In agriculture and food processing, mixing operations are often used for blending ingredients. The food processing industry relies heavily on mixing to ensure delivery of a product with fixed properties. A satisfactory mixing process should produce a uniform mixture in minimum time and with minimum cost for overhead, power and labour. Nowadays, these industries are focusing on decreasing the production time while maintaining high quality manufacturing [3].

Granular material mixing was defined as a process of dispersing a few components by chaotic, random movement of grains [1]. Complete mixing could be also defined as the case wherein all the sub-mixtures are found to contain the components in the same proportion as the original mixture. This process is one of the oldest and yet one of the least understood unit operations in process engineering. The mixing process is a result of mechanisms like diffusion, convection and shear [1, 4, 5, 6]. This process is significantly influenced by a few parameters, such as the characteristics of mixed components, the type of mixing equipment and the process conditions. This is reflected by better mixing of the components or their secondary segregation. The effect of mixing, as well as its speed are therefore functions of many parameters relating both to the mixed material and the process conditions. The parameters characterizing the properties of the mixed materials are, for example: the particle size distribution, the shape of the surface grains, bulk density, moisture content and how it is bound. Important features of the mixing device are its dimensions, the shape of the mixer and the agitator, or the type and the arrangement of the equipment for loading and emptying the mixer. Important parameters characterizing the process conditions are also share mass (or volume) of individual components, the ratio of the volume of the mixture to the working volume of the mixer, as well as the way and the order of loading the components of the mixture and mixing intensity [1]. Multithreading of this phenomenon makes it an interesting issue.

Mixing is more difficult to define and evaluate with powders and particulates than it is with fluids. For this reason, numerous models explaining the mechanisms of mixing and attempting to describe this process have been created [1]. 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 [7]. 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 [8]. Interpretation of changes occurring in time, with the use of artificial neural networks is certainly one of the latest methods, the use of which enables simulation of very complex functions. There are other useful methods which can describe the process of mixing i.e. cluster analysis [9]. Modelling of mixing and also segregation process requires the confluence of several tools, including discrete and continuum description like Monte Carlo simulations, cellular automatic computations, and often, considerably geometrical insight. Even small differences in either size or density lead to flow-induced segregation [10, 11]. Segregation problem is unavoidable in industrial condition, especially when industrial formulations are multi-component mixtures.

Multi-component 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 [1]. The majority of real granular mixtures, which can be encountered in industry, e.g. in feed mixing plants, are constituted by multi-component non-homogenous systems. Particularly in this field the mixing processes are not well understood. Most of the published research findings concern two-element or three-element arrangements. Many of these works concern the phenomenon of segregation [12 ÷ 16].The behaviour of granular materials is of great technological interest [17], and its investigation has a history of more than two hundred years. Nevertheless the basic physical understanding of granular media is far from being complete [18].

Figure 1 Mixing line in an industrial feed plant in the following unit: a feed mixer, an intake hopper and a bucket conveyor

The paper presents a possibility to use the nonlinear regression model to attempt the prediction of quality changes in a ten-component non-homogeneous granular system during mixing carried out on the mixing line in an industrial feed plant in the following unit: a feed mixer, an intake hopper and a bucket conveyor. Regression analysis constitutes the most widely and frequently used statistical method of modelling of dependences between variables [19]. Linear and non-linear regression methods are also used in other areas of agrophysics – biological, technical [20] and physical properties in evaluation of the influence of dimensional and resistance characteristics of barley kernels on the energy consumption during grinding [21]. 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 determining any type of dependence between variables.

2 Material and methods

The research was conducted on the mixing line in an industrial feed plant in the following unit: a feed mixer, an intake hopper and a bucket conveyor (Fig. 1).

Scheme of a mixer and its parameters, including the presented mixing screw inserted inside the mixer is presented in Fig. 2.

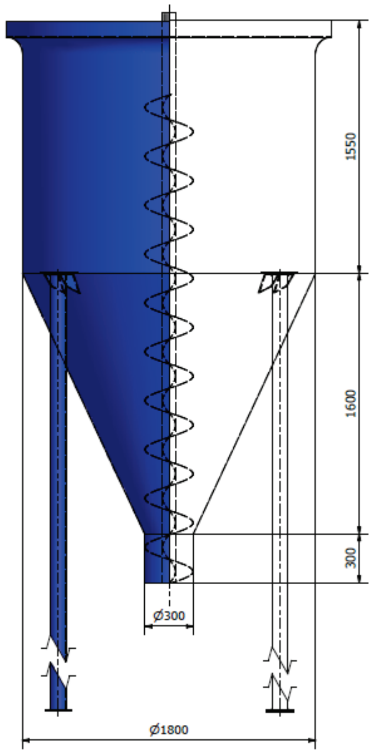

Figure 2 Scheme of a mixer and its parameters (elaborated by author)

What was characteristic for the process was the recirculation of the components by the bucket conveyor. The poured granular material was pouring out in the place of discharge, and then directed to the bucket elevator from which it went back to the mixer. Thus, the mixing took place thanks to the movements of the mixing screw and the recirculation with the external unit through the bucket elevator. The full mixing cycle was 30 minutes.

The samples for the research were taken during the mixing with recirculation every 30 seconds in the place of discharge from the mixer. The mass fractions of the research samples were converted into percentage fractions. Feed mixtures (pigeon feed) differing in the ingredients' proportions and composition (9, 11, 12 ingredients) constituted the granular mixtures used for research. Mass of the granular materials charged to the mixer equalled: 2000 kg, 2099,5 kg, 2100 kg. Composition of granular mixtures, their mass and percentage share, and the mass of components charged to the mixer are presented in Tab. 1.

Table 1 Composition of the examined compound feed

Mixture	9-element feed mixture		11-element feed mixture		12-element feed mixture	
Components of the mixture	Percent Portion / %	Mass Portion / kg	Percent Portion / %	Mass Portion / kg	Percent Portion / %	Mass Portion / kg
White sorghum	1,25	25,00	5,71	120,00	2,86	60,00
Green pea			14,29	300,00	4,76	100,00
Yellow pea	5,00	100,00	23,81	500,00	10,48	220,00
Barley	29,00	580,00				
Carthamus			2,86	80,00	1,19	25,00
Maize	16,00	320,00			40,49	850,00
Hulled oat			4,76	100,00	2,38	50,00
Field pea	10,00	200,00	20,48	430,00	16,20	340,00
Yellowmillet	2,25	45,00	7,14	150,00	7,62	160,00
Wheat	30,00	600,00				
White rice			2,38	50,00	1,19	25,00
Black sunflower	1,50	30,00	3,81	80,00	1,88	39,50
Sorghum	5,00	100,00	12,38	260,00	8,57	180,00
Brown vetch			2,38	50,00	2,38	50,00
Total	100,00	2000,00	100,00	2100,00	100,00	2099,5

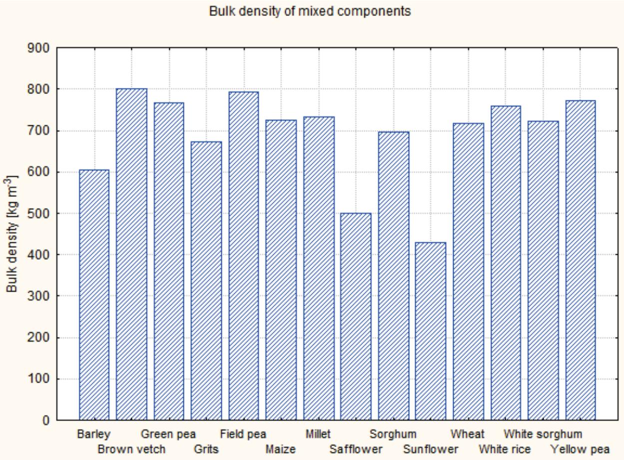

Figure 3 Static bulk density of individual components of mixtures (elaborated by author)

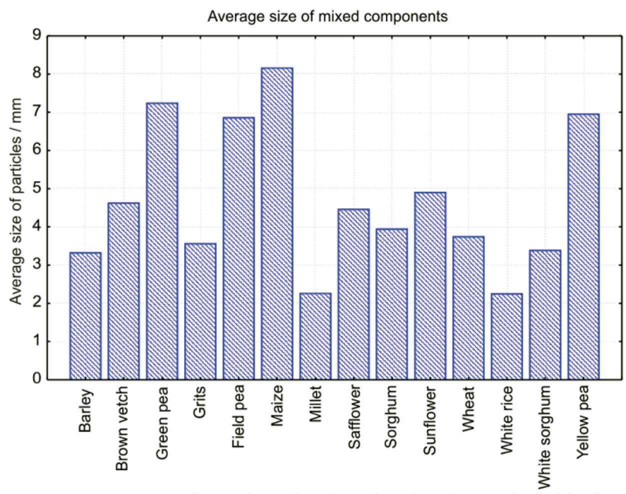

Figure 4 Average dimension of grains of grain mixtures individual component (elaborated by author)

Characteristic properties of the mixed materials are presented in Fig. 3 and Fig. 4.

Statistical bulk density ρ_n was determined in conformity to 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 PN-71/C-04501 standard.

The statistical analysis proceeded in two stages: in the first stage the quality of the mixtures was determined, in the second stage statistical modelling was done by means of nonlinear regression.

Analysis of percentage changes of the components' share in the mixture inclined to searching for a parameter, which would determine the mixture's quality in a certain unit of time with only one universal numerical value. The residual sum of squares was used as a parameter for description of the mixture's quality. The qualities of granular mixtures were described this way in the authors' previous articles [22, 23].

A classical linear regression model was used for description of the mixing process. The basic equality of variance analysis is the following dependence:

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

where:

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

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

$\sum_{j=1}^{n}(y_j-\hat{y}_j)^2$ – the residual sum of squares of the Y response variable's deviations (SSE or RSS) [24].

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:

$$RSS=\sum_{i=1}^{n}e_i^2=\sum_{i=1}^{n}(y_i-\hat{y}_i)^2, \tag{2}$$

where:
RSS – the residual sum of squares
e_i – error
i – observation
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.

The paper presents a possibility to use the nonlinear regression model to attempt to predict the quality changes in a ten-component non-homogeneous granular system during mixing carried out on the mixing line in an industrial feed plant in the following unit: a feed mixer, an intake hopper and a bucket conveyor. Modelling was carried out for dependent variable and two independent variables.

Dependence between the residual sum of squares, the number of the mixture's components (9, 11 and 12 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 (9, 11 and 12 components), independent variable.

It was reported that dispersion of empirical data reflects the course of dependencies of square function, which may be described with a 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 of two independent variables:

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

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 Statistica software in the "nonlinear estimation" module of the programme [25]. Matching the empirical values to the modelled values was estimated with the least squares method for parameters of function with a formula (5). The chosen method of estimation was to minimize the residual sum of squares (differences in the values observed and identified by the model) in order to find the best fit parameter set and to estimate the standard errors for parameter estimators. For the purposes of the nonlinear least squares regression (i.e., to match a nonlinear function with the loss function of the least squares) an algorithm was used, namely the Levenberg-Marquardt method [26, 27, 28]. It is a frequently used algorithm, it constitutes an improved version of the Gauss-Newton algorithm for least-squares, used when solving nonlinear regression problems [29]. This is a recommended algorithm for nonlinear regression issues, more efficient than other, more general optimization algorithms (such as the Quasi-Newton algorithm or the simplex method). There is no need to calculate (or approximately estimate) the second order partial derivatives in the application of the least squares loss function to find the parameter estimates. Instead, at every step the algorithm solves the linear system of equations for calculating the gradient, which is computationally relatively easy and fast (compared to other optimization techniques) [28]. Due to the introduction of the parameters' estimation procedure, obtained results were in the form of regression coefficient values of the assumed model, the assessment of the statistical significance for the obtained regression coefficients, 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. 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 [30]. 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. For the final evaluation of matching the model in the nonlinear estimation of three variables (two predictors), the option of the matching function was applied with the use of the final parameter estimates. Based on the obtained formula of quadratic function with specific parameters, the prediction of quality changes in a ten-component granular mixture was made.

3 Results and discussion

The obtained values of the residual sum of squares for the examined 9, 11 and 12 component mixtures are presented graphically in Fig. 5.

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

$$\begin{aligned} z = (0{,}59 \cdot e^{-4}) \cdot x^2 + (-1{,}04) \cdot x + 0{,}08 \cdot x \cdot y + \\ + (-107{,}74) \cdot y + 1473{,}59, \end{aligned} \tag{6}$$

where:
z – residual sum of squares,

x – mixing time, s
y – number of components.

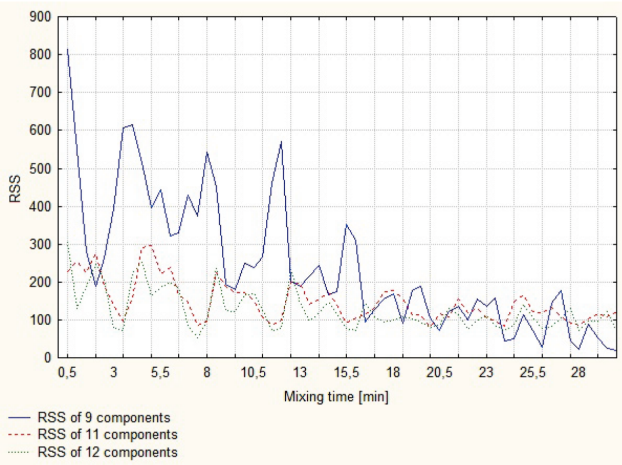

Figure 5 The graph showing changes in the residual sum of squares, depending on the mixing time obtained for mixtures of 9, 11 and 12 components (elaborated by author)

The presented values of regression coefficients were determined based on the level of significance (alfa = 0,05). The resulting regression coefficients were, respectively: $a = 0{,}0000586$, $b = -1{,}0389$, $c = 0{,}075093$, $e = -107{,}74$; $f = 1473{,}59$, while the regression coefficient d is omitted in the model because this value is not statistically significant. The obtained coefficient of determination equals $R^2 = 0{,}80$.

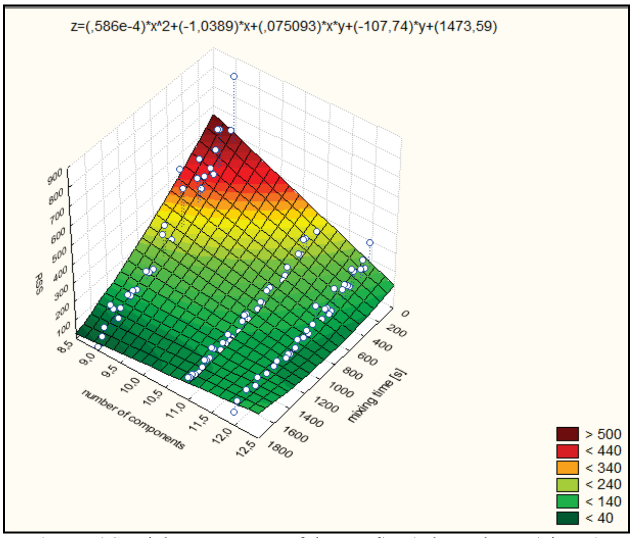

Figure 6 Spatial arrangement of the $z = f(x, y)$ dependence (view a)

Below there is an obtained 3D (three dimensional) chart for the two predictors in two different views (Figs. 6 and 7).

In Fig. 6 and Fig. 7 spatial arrangement of the $z = f(x, y)$ dependence obtained as a result of statistical modelling is 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 Eq. (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=0,80 shows that the empirical data were quite properly adjusted to the nonlinear regression model. The scheme (Fig. 8) shows, that with the greater number of components (9) the quality of granular mixture is the worst in the last phase of the mixing process.

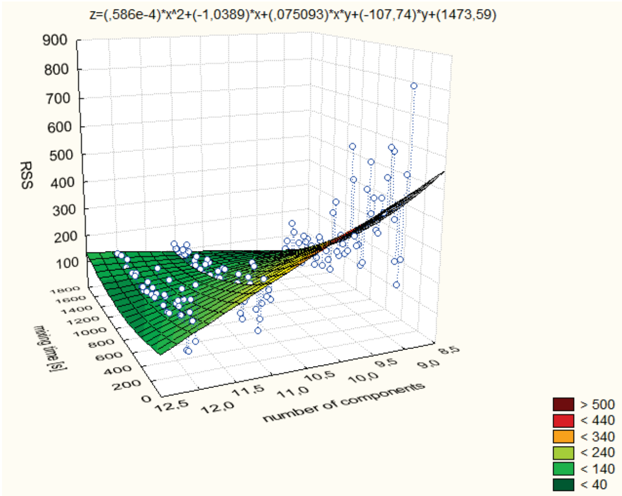

Figure 7 Spatial arrangement of the $z = f(x, y)$ dependence (view b) (elaborated by author)

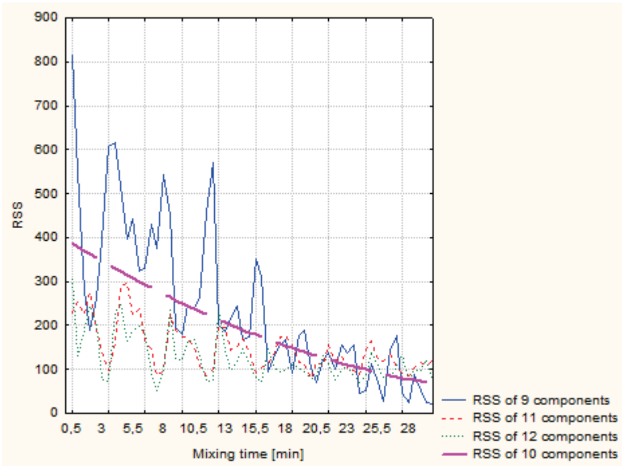

Figure 8 Graphical interpretation of the predicted course of quality changes during mixing for a 10 component granular mixture not tested in the experiment (marked with dashed line)

From the middle of the mixing process, after 15 minutes, the quality of mixtures is similar. The proposed model may constitute an attempt to predict quality changes in a ten-component granular arrangement on the mixing line in an industrial feed plant before the commencement of the mixing process. The linear regression model Eq. (6) was used to develop a chart (prediction) of changes in the residual sum of squares parameter during mixing for 10 components of the mixture (Fig. 8). 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. This would call for further experimental studies of mixtures of different compositions of feed and different number of components.

4 Discussion

Referring to the methodology adopted for the experiment it is necessary to comment on several issues: the method of sampling, the quality assessment method, and the attempt to model the relation between the studied variables: residual sum of squares, mixing time and the number of mixture components.

Sampling took place at the outlet of the mixer. Traditionally, sampling takes place at various depths of the bed and it is done by a sampler. There are also other techniques enabling assessment of the quality of the end product such as more and more popular method of computer image analysis. Tukiendorf's research proposes and presents indicators that can be used in the description of heterogeneous quality of binary systems stored in silos [7, 8]. In his work, he emphasized that in assessing the quality of granular materials (such as feed, mix, precast) stored in a silos, it is necessary to assess the state of mixing in all directions. It is therefore necessary to introduce measures based on indicators, arising from all degrees of freedom, which particles of these systems (longitudinal and transverse directions) have. The indicators used to assess the quality result based on observation of the distribution of a key component in the vertical plane only are unreliable and can introduce incorrect information. Measures resulting from indicators suggested so far by inter alia: Rose, Danckwerts, Lacey and others require the discussion on the evaluation of their use. Tukiendorf suggested as an alternative to these methods, a description of the quality of granular mixtures involving the simultaneous comparison of the distributions of transverse and longitudinal variance and the value of tracer concentration on the surface of the observed cross sections. In the experiment sample collection at the bottom outlet of the mixer seems to be the most convenient place, because it is the end of the technological process.

The sampling method is related to the issue of choosing a measure for quality assessment. Previously mentioned several measures of evaluating the quality and the most common method of assessment is a measure of Rose [31]. Availability of increasingly modern electronic techniques tends to use less labour-intensive methods of assessment that is the computer image analysis. However, research presented in the experiment described in this paper due to the considerable amount of the components tool for image analysis did not apply. Samples division into individual components were thus made manually.

The synthetic analysis of the results shows that the longer the mixing time, the better mixture quality is (Fig. 5). This is not an obvious statement, because during the mixing of granular materials secondary segregation process is often found which causes deterioration of quality over time of mixing. Changes in quality of the mixtures do not have the typical character of the changes, such as a linear function or logistic function. The nature of quality changes in time are rather of a "hock", change, consisting of the periodic fluctuations of quality changes. A hypothesis may be drawn, that this shape of changes is caused by the operation of the screw agitator that is placed inside the mixer. In the process, the mixer operates in a continuous manner. It can be assumed that the layer of components is formed in the mixer, and it is strictly related to the process of filling the components into the mixer. It should be considered as collections of buried up seed as practically, filling process consists of several stages. First, ingredients with diameters of larger sizes stored in a silo are loaded into the mixer together − they are also the ingredients that constitute the greater percentage of the mixture. Then the ingredients of different sizes of grains are poured into mixer, which are stored in bags and their participation in the composition is relatively small. The quality at some moment of time improves greatly, and then the quality worsens, and again after some time the quality improves (Fig. 5). It can be observed that the quality in the first 15 minutes of mixing is much worse for the mixture consisting of 9 components. The nature of quality changes for a system consisting of 11 and 12 components is similar. Analysing the chart, one can also notice a gradual stabilization of quality changes after about 15 minutes of mixing.

The proposed model may constitute an attempt to predict quality changes in a ten-component granular arrangement on the mixing line in an industrial feed plant before the commencement of the mixing process. Linear regression model (model 2) was used for developing a chart (predicting) changes in the residual sum of squares of the parameter when mixing for 10 components of a mixture (Figs. 6 ÷ 8). Graphs (Fig. 6 ÷ 7) show that the model is quite well suited for quality changes for the arrangements consisting of 11 and 12 elements, and not so well suited for the 9 component mixture system. However, the coefficient of determination for the model R^2 = 0,80 indicates a fairly good fit of empirical data to nonlinear regression model.

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. Due to little amount of available literature concerning the mixing of multicomponent heterogeneous systems any observations, findings explaining the mechanisms of mixing contribute to widening the knowledge in this field of science. An attempt to find relations between variables made in this paper does not exhaust the problem of multithreaded phenomenon, where the manner and the process of mixing are influenced by many parameters. The studied literature indicates that the greatest impact on the occurrence of segregation is a significant difference in diameter and density. The reasons for the different waveforms of quality changes in time should therefore be seen as in the composition (recipe) of the mixture, and therefore the ratio between the densities and mean particle sizes. This would call for further experimental studies of mixtures of different compositions of feed and different number of components.

5 Conclusions

1) Linear regression model in the form of the described square function reflects well the quality changes of mixtures in time, which is proved by the high value of the coefficient of determination R^2 = 0,80.

2) The developed regression model enabled prediction of quality changes of a granular mixture in a 30 minute mixing time for a ten-component mixture, which was not the object of the study.
3) The applied statistical methods – residual sum of squares and nonlinear regression constitute appropriate tools for analysing the mixing process in multi-component granular systems.

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Author's address

Jolanta B. Krolczyk, PhD. Eng.
Department of Agricultural and Forest Technology
Opole University of Technology
5 Mikolajczyka Street, 45-271 Opole, Poland
E-mail: j.krolczyk@po.opole.pl