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CHARACTERISTICS OF MIXING GRANULAR MATERIALS ACHIEVED BY USING METHODS OF VARIANCE ANALYSIS AND GEOSTATISTICAL FUNCTIONS

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ABSTRACT

The article proposes the original way of evaluating the distribution of granular mixture particles after mixing by funnel-flow system. On the basis of graphical analysis of the picture first the observation of value changes of variances in particles distribution along radius of mixer cross sections has been made. Basing on chosen cases of mixing steel and mustard particles it has been shown that the character of these changes is different for various mixing ways. It can be described approximately by non-linear mathematical functions. Similarity between the distributions variances and the applied non-linear functions depends on the correlation coefficient. To describe properties of mixing granular materials geostatical functions (G, $\hat{F}$, K) have also been adopted and presented. The application of this method has also been shown for tracer distribution in the mixer. The results of investigation for particular functions have been presented in the form of graphs and were discussed.

Key words: mixing of granular materials, *funnel-flow* system, distributions of particles in the cross sections of the mixer, analysis of variances, computer analysis of the pictures, geostatistical functions

INTRODUCTION

Mixing as an operation in granular material technology

During mixing of granular materials using different methods, due to the specific physical properties the components are located in certain places in mixed bed. The purpose of mixing is to conduct the systems different in densities and dimensions to the dynamic stable state, however, it is important that distances between mixed parts of the same components must be equal. A chess board pattern can be an example of the surface distribution of two-component granular system mixed ideally. Unfortunately, segregation – a phenomenon that is counterbalancing the homogeneity causes that the achievement of such a mixing state, especially in non-homogenous conditions of materials is impossible [1, 3, 19, 27, 29, 30, 37].

In the mixing of granular materials that are widely used in the agricultural and food industry, a process of the mixed components' allocation in the whole volume of bed is one of the most important issues [13, 20, 21, 22, 23, 24, 25]. Due to the fact that up-to-now a universal determination of mixing of such systems has not been found, a predicting of particles allocation during the mixing is considerably difficult. The mixing of granular materials exposes the following processing properties: kinetic [26, 36], diffusive [18] and random [4, 12]. In each model the introduction of constant parameters characteristic for certain conditions (e.g. time parameters) is indispensable. However, these parameters can also be determined through the marginal conditions effectively not limiting the universality of the proposed methods [2, 28]. For mixing methods the models were established only theoretically with small application achievements. In such a context, scientific attempts to depict complex mixing of granular materials are of great importance.

In the agricultural engineering, the permanent and periodical mixing is conducted in relation to technological requirements. The devices created for such processes have different dimensions and work in different times as well. They also have different effectiveness respectively. Consequently, a behavior of mixing elements as well as properties of granular materials themselves have an influence on granular element location [5, 11, 30]. In this light, analytical methods based on variance distribution analysis as well as on modern geostatistical solutions in modeling distribution states during mixing seem to be fully justified.

Mixing by the *Funnel-Flow System*

The mixing can be conducted in a variety of ways, which are divided into two groups: a permanent mixing and a periodical one [3]. In case of periodical mixing, a granular material flows into the mixer, then the mixing is conducted up to the achievement of equilibrium state, after which the following mixing does not cause any quality changes in a bin. One of the examples of this type of mixing is based on discharging the granular material from a one bin into another. This method is called a "funnel-flow" system and it is an inexpensive and very efficient method of mixing, especially in the conditions of large material volumes [3, 8, 9, 30]. A material can disperse in a bin in different ways. In case of large differences in material densities, the heavier component indicates a propensity to sink in a lighter one. Consequently, the heavier component is located in lower bin sections. Whereas, homogenous materials are dispersed equally in the whole bed volume, giving the picture of randomly but equally distributed grid in longitudinal and cross sections (fig. 1) [30].

Fig. 1. Equal distribution of the mixed granular material (longitudinal sections; aluminum oxide-aluminum oxide system) [30]

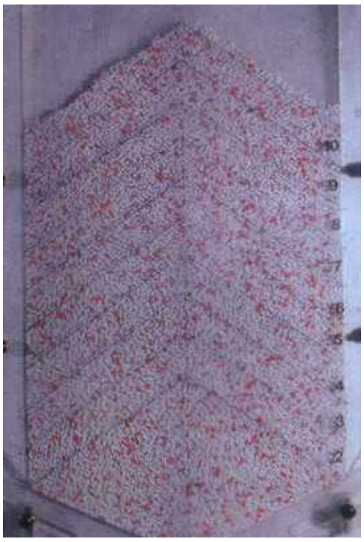
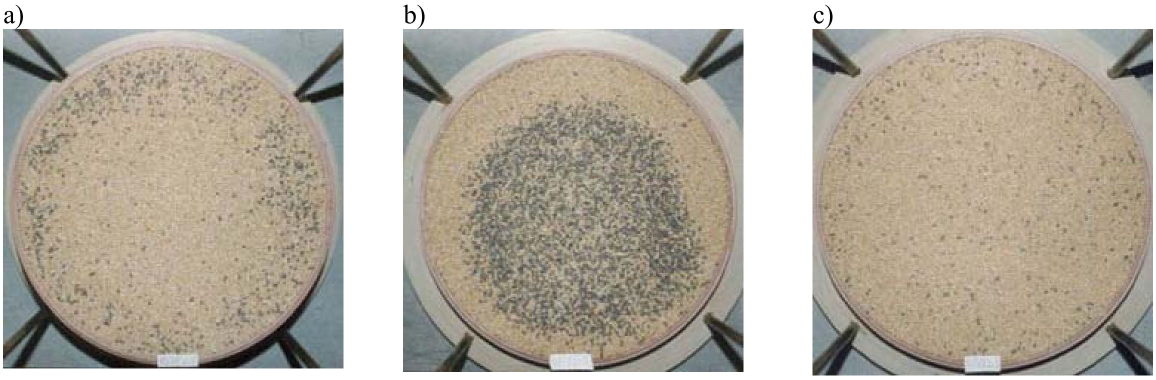


Fig. 2. Types of concentration distribution of granular components during mixing by *Funnel - Flow System* at chosen cross sections of mixer. Steel particles-mustard granules system $\rho_1/\rho_2 = 6.25$: a) core mixing, b) ring mixing, c) random mixing [32]



A distribution in longitudinal sections is easy to observe, especially in situation when the transparent mixer walls are built-in. However, a distribution of a granular material in cross sections is difficult to detect and it depends on the height at which the observation is performed [34]. Granular material indicates different but constant tendencies in certain locations on the surface. These tendencies depend on already mentioned physical properties of the parts as well as on the used elements supporting the mixing (for example *Roof Shape Inserts*) [10, 33]. Roof Shape Inserts applies in the bin axis in their upper inlet sections. Granular materials flowing from one bin to another and hitting the surface of the insert changes trajectory of the movement. Due to different grain diameter bigger grains achieve bigger torques which in turn causes that they take different from usual (during free flow) locations in the bin. A proper choice of angles of flare of inserts allows to achieve various grain distributions which can take certain characteristic locations in extreme situations. Due to earlier research the locations were defined. Boss and Tukiendorf [6, 31, 32] proposed using the following terminology: ring distribution when the material gathers mainly on the borders of the section, core distribution when the material fills in the middle and random – is placed on the whole surface equally (figure 2a-c) [32].

THE AIM OF RESEARCH

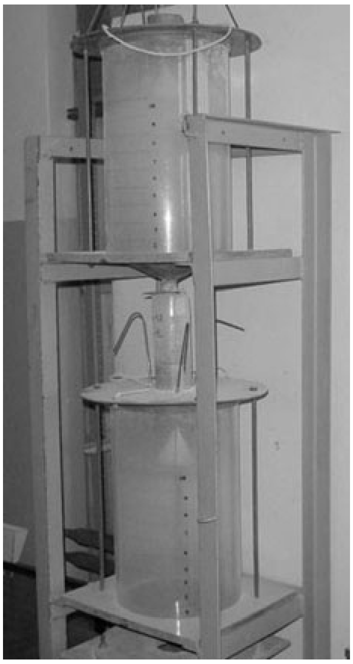
The aim of the research was to propose and to evaluate the methods of defining the way of grain distribution in the chosen cross sections of bins. As the results of RSI system application distributions were different. Random but on the other hand, characteristic distributions observed and photocopied during mixing steel particles - mustard granules have been chosen (fig. 2). It has been assumed that the proposed methods will be universal and their application will be simple and effective in the technology of mixing heterogeneous granular systems.

METHODOLOGY AND RESULTS

Experimental set-up

The precise description of the experimental set up (fig. 3) used in this research can be found in [7, 8, 9, 30].

Fig. 3. ***Funnel – Flow System*** **Mixer**



Mixing was based on discharging the granular materials from bin to bin. The bins changed places after each step of mixing. In such a way that input bin became the output one and vice versa. The process was continued during 10 following steps. It has already been proved that number of 5 successive steps is enough to achieve equilibrium states [8, 9, 30]. Steel particles were mixed with mustard in the proportion 1:9. Before mixing steel particles (tracer) were placed in the middle of the input bin while the mustard particles were put in the upper and lower tracer. Big density difference (ρ_1/ρ_2 = 6.51) made mixing difficult causing strong segregation effects. Heavier steel particles gathered in the lower parts of the bins [9]. The research was conducted with and without the application of Roof Shaped Insert System. The system strongly affected the changes in particle distributions. The distribution of steel particles could be observed on the chosen surfaces of 10 bin cross sections as the bin for the final analysis was built from 10 loose elements put one on another. After each mixing process the elements were taken off from the upper to the lower one. The surface of each section was filled with the mixing granular system. While taking off each element the material was removed layer after layer in such a way that it didn't disturb the granular load remaining in lower sections of the bin. The analyzed pictures were taken photo of and transferred to digital computer memory. It has been proved that there is a big dependence between the concentration of the trace color distribution and its volume participation in the sample [6, 31, 32].

Each of the two applied methods was based on digital picture analysis. In the first method evaluation was based on the variance change analysis along the radius cross section for three of the chosen grain distributions. In the second method to describe the distribution of one random cross section several geostatistical functions have been applied.

With the use of proper spatial point pattern analysis functions properties of steel particles dispersed in mustard grains distribution have been defined. The investigations were made on the basis of digitally visualized points.

The evaluation of granular distribution by variance analysis

The graphical analysis was conducted using Krótkiewicz's PATAN software and it was based on the estimation of the color intensities of cross sections surfaces. In the study, the whole surface was covered by multi-elemental grid [15, 16, 17, 35]. Then, for each element, the distribution variance for the observed granular component was calculated. For the purpose of the presented analysis, the number of hundred elements was supposed to be sufficient for the 30 cm bin's diameter (figures 3, 4, 5, 6).

It is well known that bigger the variance is the more distant from the ideal pattern the distribution is ("chess board" $\sigma^2 = 0$).

The comparison of the tracer's distribution variances for the three different cross sections was available after their normalization following the estimation of relative variances from the absolute ones

$$x_n = \frac{x_i - x_{\min}}{x_{\max} - x_{\min}} \text{ for } i,n = 1,\ldots,10$$

where:
x_i – denotes the empirical concentration at the *i*-th element,
$x_{\min}$ – the lowest empirical concentration for all elements,
$x_{\max}$ – the highest empirical concentration for all elements, and
x_n – the normalized concentration for the *i*-th element.

The equation (1) constraints the normalized variances into the [0;1] interval. The evaluation of changes for concentration distributions was performed based upon the increase of variance for the circles with the growing radius. The five radiuses with electronically measured length were taken into account: r_1 = 100 pixels, r_2 = 200 pixels, r_3 = 300 pixels, r_4 = 400 pixels, r_5 = 460 pixels. Next for the analyzed surfaces, the variances of the tracer's distribution for the particular cross sections were computed.

Fig. 4. Ring distribution; determination of the analyzed surface for the variance estimation of the tracer's distribution radius lengths: a) r_1=100 pixels; b) r_5 = 460 pixels crude map. Tracer's share in gray-scale for the various radius lengths: c) r_1=100 pixels; d) r_5 = 460 pixels

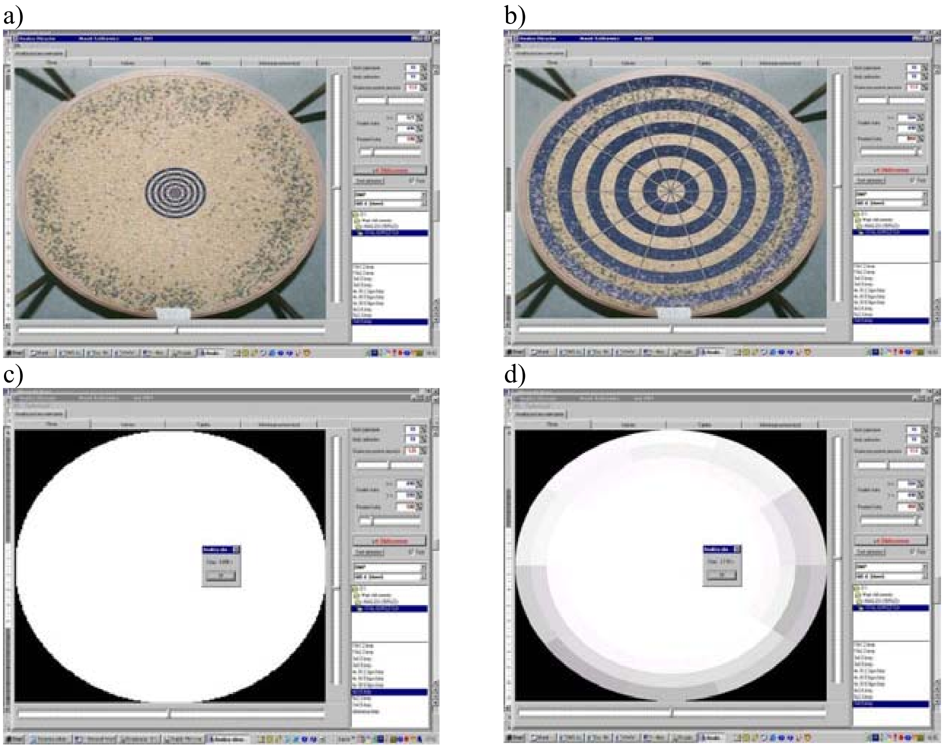
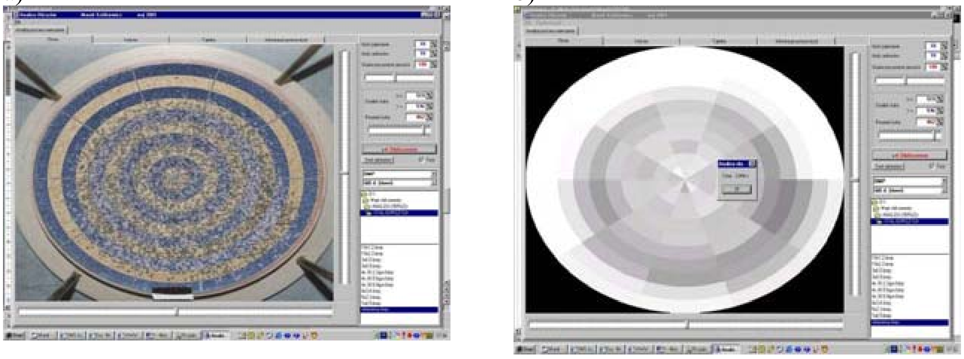


Figure 4a shows the picture of the cross section covered with 100 element grid of the radius r_1 = 100 pixels. Figure 4c shows the concentration analysis of steel particles made by computer program. On the surface of the cross section the program doesn't recognize changes in color intensity in gray scale. What is more the background is definitely light, that means we can not observe steel particle concentration essential enough the occurrence of which would cause the increase in intensity of gray color. Figures 4b and 4d concern the analysis of concentration of steel particle distribution on the whole surface of cross section (radius r_5 =460 pixels). The change of gray color together with the increase of grid radius corresponds with value changes of concentrations occurring in these places of steel particle. Variance values of concentrations in the both cases presented in Figure 4 must be different and what seems to be justified they should change with the change in length of the radius of the analyzed field. This property has been assumed as the basis for further investigations. Steel particle distribution has been observed and that is why variance values of its concentration in the fields with the increasing radius lengths, were estimated. The investigations have been conducted on the surfaces of 3 chosen granular sections (see figure 2).

Figure 5 shows the analysis of the picture after mixing when core distribution is achieved. Radius length of the observed analytical field is maximum (r_5 = 460 pixels). With reference to the whole radius length essential intensity in gray color in the core of the field can be seen. Boundary of the cross section is free from big steel particle concentration. It can be assumed that the next distribution variances evaluated for 5 increasing radius lengths will undergo some changes respectively.

Fig. 5. Core mixing; determination of the analyzed surface for the variance estimation of the tracer's distribution radius lengths: a) r_1=460 pixels; b) r_5=460 pixels distribution of tracer in gray scale

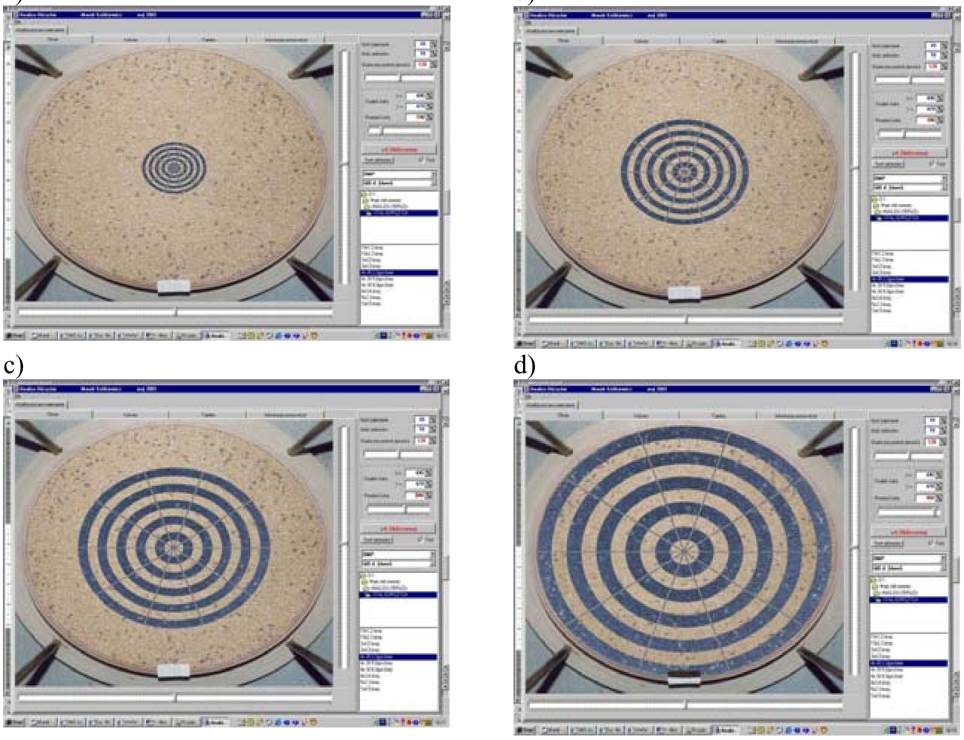


a)

b)

Figure 6 shows the case of the analysis of cross section picture after mixing when random distribution is achieved. The photos show steel particle distribution in the observed fields (radius from r_1 = 100 pixels to r_5 = 460 pixels).

Fig. 6. Random mixing (determination of the analyzed surface for the variance estimation of the tracer's distribution; hundred-elemental net; radius lengths: a) r_1 = 100 pixels; b) r_2 = 200 pixels; c) r_3 =300 pixels; d) r_5 =460 pixels



a)

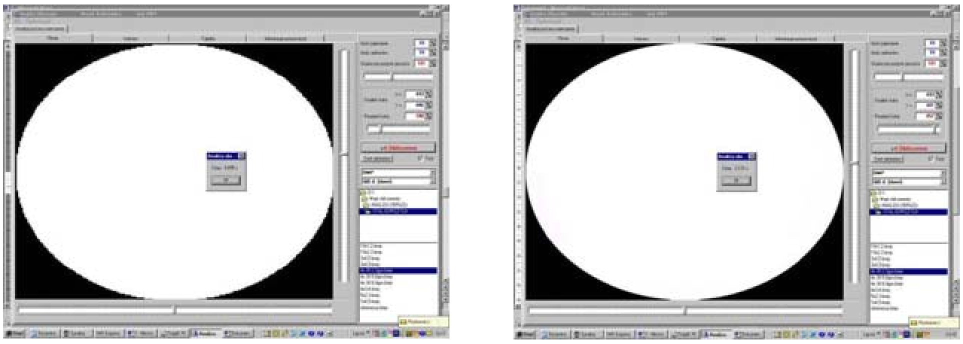
b)

c)

d)

Figure 7 shows the random distribution of steel particle concentration after mixing in gray scale (radius from r_1 = 100 pixels to r_5 = 460 pixels).

Fig. 7. Random mixing. Tracer's picture for the radius lengths; Tracer's share in gray-scale for the radius lengths: a) r_1=100 pixels; b) r_5=460 pixels



The light shade of gray color distribution on the surface of the analysis cross sections proves that both in the field of short (r_1 = 100 pixels) as well as long (r_5 = 460 pixels) radius steel particle distribution is detected by the analyzed program as even.

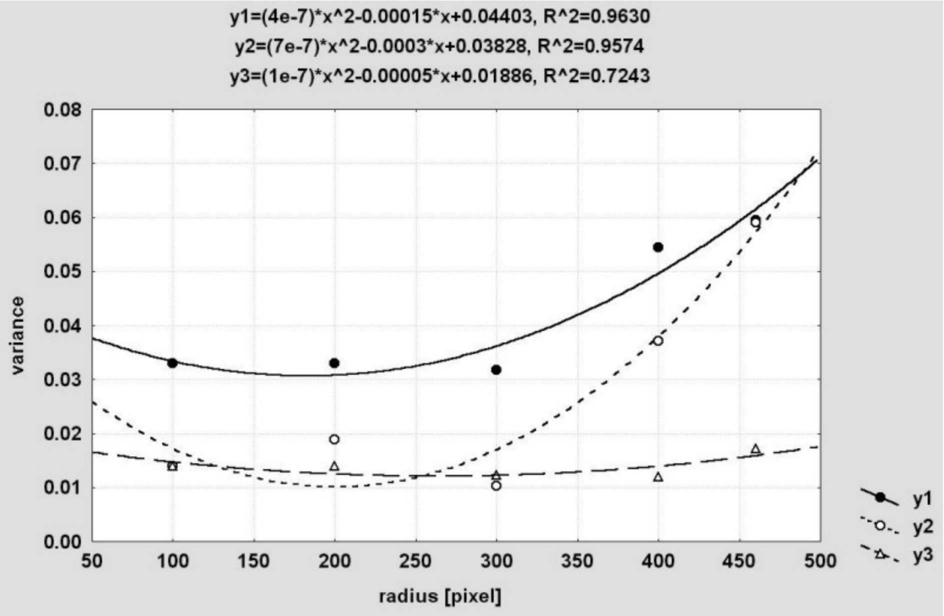
Variance Analysis Results. The variances of the tracer's distribution in relation to the radius length (for r_1 = 100 pixels; r_2 = 200 pixels; r_3 = 300 pixels; r_4 = 400 pixels; r_5 = 460 pixels). The variances were estimated basing on values corresponding with gray shades in the points of the 100 element measuring grid, according to *RedGreenBlue* scale (0-255).

Table 1. Variances of tracer's distribution in relation to the radius length and type of surface mixing

mixing type/radius [pixel]	100	200	300	400	460
core distribution	0.0330	0.0330	0.0317	0.0544	0.0594
ring distribution	0.0139	0.0189	0.0103	0.0371	0.0590
random distribution	0.0140	0.0139	0.0122	0.0119	0.0172

Figure 8 shows that in case of the random distribution, the regression curve y_3 indicates the stagnancy across the radius length and does not change in the interval from (r_1 = 100 to r_5 = 460 pixels). Its shape testifies to a good dispersion of the key component in the studied cross section.

Fig. 8. Changeability of variances of tracer's distribution in relation to the radius length and type of surface mixing (with polynomial fits and R^2): y_1 – random; y_2 – ring; y_3 – core



The curve y_1 concerns the core distribution. The first three points on the basis of which the curve was estimated show that the variances ($var_1 = 0.0330$; $var_2 = 0.0330$; $var_3 =$ 0.s0317) were very similar to each other and they present the core as the most concentrated part of the surface. The next variances increase with the radius length and this fact has a direct relation to the tracer's share which considerably decreases ($var_4 = 0.0544$; $var_5 = 0.0594$).

The latter effect causes the important change of variance in relation to the whole analyzed bin cross section ($r_5 = 460$ *pixels*).

The curve y_2 shows the trend for the consecutive variances with the increase of the radius length for the ring type of mixing. The first three points referred to the tracer's distribution in the middle of the cross section ($r_1 = 100$; $r_2 = 200$; $r_3 = 300$ *pixels*), show the very similar variances ($var_1 = 0.0139$; $var_2 = 0.0189$; $var_3 = 0103$). They inform that the tracer's distribution is not equal although the tracer is present marginally. Moreover, a strong increase of the variances ($var_4 = 0.0371$; $var_5 = 0.0590$) at consecutive radiuses ($r_4 = 400$ and $r_5 = 460$ *pixels*) proves that the change of density of granular material has occurred (see the ring with the congested granules).

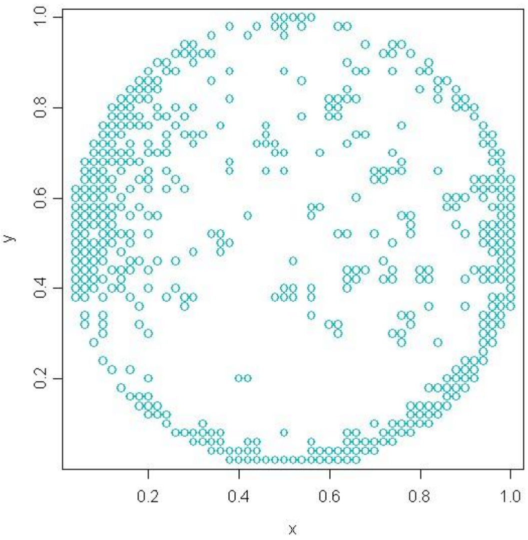
Geostatistical Functions in the Description of Properties of Granular System Mixing

Analyzing spatial point patterns. Taking onto account that a spatial point pattern is a collection of points irregularly located within a boundary region of space it can be assumed that the points can denote locations of naturally occurring phenomena such as environmental as well as experimental. The data may consist of locations only, or it may be a marked point process, with data values associated with each location (mark). An example of a marked point process is a set of locations of a specific type o a tree among another tree species distributions in a forest. Thus, the analysis can be adopted mixing of granular materials. In the presented study, the observation of surface distribution of the steel particles among the dispersing phase of mustard grains during the mixing process. The picture of the steel particles distribution was digitally visualized following the RGB (red-green-blue) scale. The darkest pixels – i.e. the lowest RGB values were assumed to be the marks of the point process whose associated locations were used to:

- examine point patterns for complete spatial randomness (G- and F-functions),
- calculate Ripley's K-function.

Picture analysis and results. Figure 9 shows an example of the steel particles distribution in the chosen cross section generated during the mixing of granular materials.

Fig. 9. Scatterplot of the tracer's locations for the mixing data



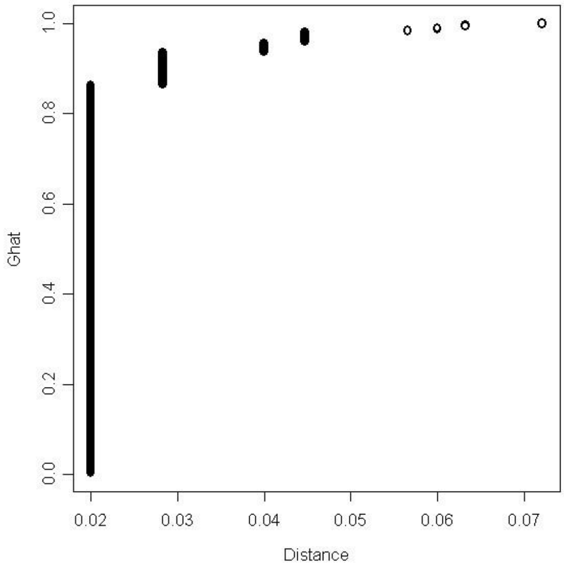
A visual point pattern analysis provides evidence of clustering that appeared at certain stage of the mixing, however, the picture is very dense and any spatial pattern is immediately obvious.

Nearest neighbor distances provide an objective method for looking at small interactions between points. Defining a nearest neighbor distance d_i as the distance from the ith point to the nearest other point in A – the boundary region, the empirical distribution function (EDF) of these point-to-point nearest neighbor distances can be used for comparison to a complete spatial randomness process. The EDF is:

$$\hat{G}(y) = n^{-1} \sum_{d_i < y} 1 \qquad (2)$$

where n is the number of points in A. For the analyzed picture, the following plot of the $\hat{G}$ function was achieved (fig. 10).

Fig. 10. Plot of the EDF of point-to-point nearest neighbor distance for the mixing data



In the plot given above (fig. 10) an excess of low distance neighbors is observed. This rather provides evidence of clustering. (An excess of high distance neighbors is characteristic for regularity in the spatial data).

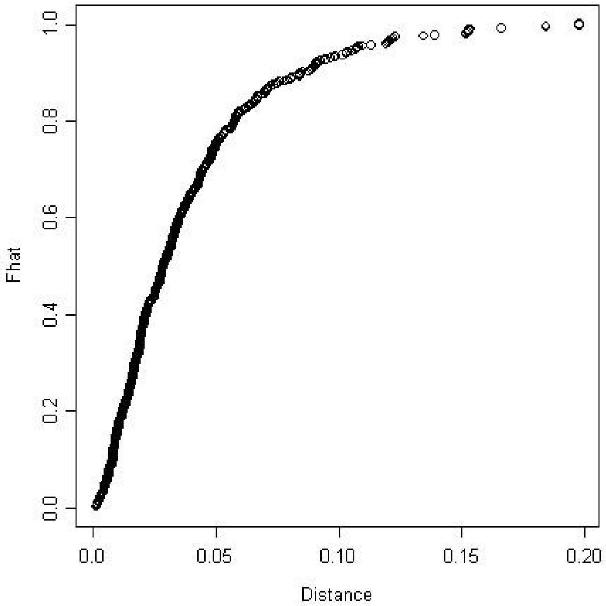
An alternative to the $\hat{G}$ test statistic can be the other one that is defined by overlaying a $k \times k$ grid on the analyzed region A, then comparing the distances from the m resulting origins to their nearest neighbors. The EDF of this origin-to-point nearest neighbor distance is:

$$\hat{F}(x) = m^{-1} \sum_{e_i < x} 1 \qquad (3)$$

where e_i is the distance from the ith origin to the closest of the n points in the data.

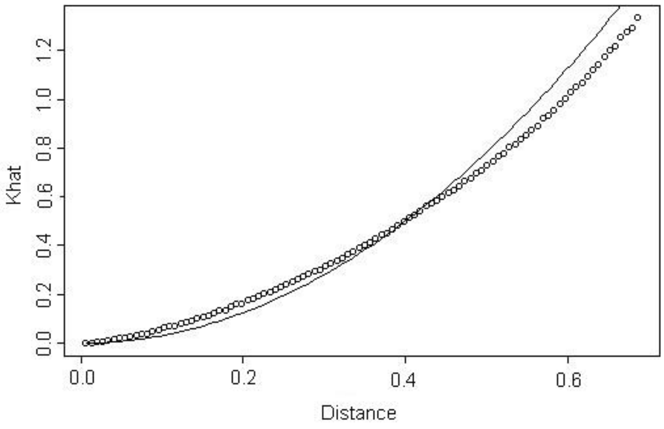
For the picture given in figure 11 the following plots of the $\hat{F}$ function were found.

Fig. 11. Plot of the EDF of origin-to-point nearest neighbor distances for the mixing data



It is of note that implementation of the $\hat{F}$ plot (fig. 11) is opposite to that of the $\hat{G}$ plot (fig. 10). An excess of high distance values is interpreted as clustering, while an excess of low distance values is typical for regularity. Then, the EDF showed in figure 11 rather provides evidence of clustering.

Fig. 12. Plot of the mixing data *K*-function



The properties of spatial point process describe how the interaction or spatial dependence between events varies through space. An easy description of these properties is defined by the *K*-function:

$$K(d) = \lambda^{-1} E \quad [\text{number of events} \leq \text{distance d of an arbitrary event}]. \quad (4)$$

where λ is the intensity (number of points per unit area), and E[number of events ≤ distance d of an arbitrary event] denotes the expectation. The advantage of the *K*-function is that the theoretical value for $K(d)$ is known for several useful models of spatial point processes. For example, the *K*-function for a homogenous process with no spatial dependence is πd^2. If there is clustering, an excess of events at short distances would be expected, leading to $K(d) > \pi d^2$ for small ds. Similarly, it would be expected $K(d) < \pi d^2$ for a regularly spaced pattern. The calculated *K*-function plot for the analyzed mixing data is showed in figure 12.

CONCLUSIONS

1. The presented findings concerning the observation of changes in value variances together with the increase in cross section radius length, show the usefulness of the photographic analysis in quality evaluation of granular materials' distribution. The method provides fairly sufficient information on location and concentration of the observed granular material. In addition because of many difficulties concerning value estimation of such systems in granular material technologies the method is fast and inexpensive in use.
2. The presented example proves that the use of geostatistical methods can play a significant role in food/rural technologies of granular materials especially as regards modeling of mixing effectiveness. Moreover, the achieved results provide evidence that G, F and K-functions presented in the study are fully acceptable for such purposes and they can be implemented to describe a dynamics of mixing at certain stage of this process and profile. It is worth noting that for a fast evaluation of the mixing states, a digital picture of a granular bed and supplied appropriate computer software – e.g. a S+SPATIALSTATS – are the only required conditions to perform such geostatistical analyses [14].

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