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Research on the impact of mass fractions of multi-element granular structure on the mixing process

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A b s t r a c t. Knowledge concerning mechanisms that govern the mixing process of multi-element heterogeneous granular structures is still not sufficient. The description of a mixing process where one of the factors is the randomness of particle motion causes additional difficulties. In the article, the authors make an attempt to describe the mixing process of a nine-element system which is a collection of grains of different characterization, among others, the size of grains, densities, or the shape of the mixed elements. In order to describe the process, the cluster analysis is used and thanks to this, homogeneous subpopulations are distinguished out of items originating in heterogeneous population. In the described case, the heterogeneous population is the output data matrix in which to each element of the mixture there is assigned the percentage portion of the elements after 30 min of mixing obtained during the research. The research was carried out in industrial conditions in a vertical mixer with worm agitator. The total mass of the mixed material was 2000 kg. The dendrogram analysis illustrating taxonomic distance between the elements of the mixture allowed to describe which of the elements had the greatest impact on the course of the process in the researched device.

K e y w o r d s: granular material, heterogeneous granular structure, multi-element granular structure, cluster analysis

INTRODUCTION

The mixing process is a particular unit operation performed in a great range of practical applications and in every processing industry. Its role is extremely important, especially when new technologies or higher expectations concerning product quality occur. In spite of the fact that many researches have been conducted, mixing of granular material is still a relevant issue. It is a complex process dependent on a variety of parameters such as: characteristics of the materials mixed, the type of mixing device used, and the conditions in which the process is conducted. What cannot be forgotten is the fact that it is also a random process during which the elements are scattered in the mixer by chaotic, random particle motion (Boss, 1987). The complexity of the phenomenon makes the problem worth analysing by a researcher. Until now, many proposals explaining mixing mechanisms have been presented. Nevertheless, a majority of the research was related to models and works carried out in laboratory conditions (Alexander *et al*., 2001; Boss and Dąbrowska, 1983; Boss and Tukiendorf, 1997; Dury and Ristow, 1997; Królczyk and Tukiendorf, 2005; Moakher *et al*., 2000; Tukiendorf, 2003). On this basis, it was possible to come closer to particle phenomena and mechanisms. None of the models is perfect and each of them has its defects and advantages. It is also known that the results, as well as the conclusions from modelling of a process in laboratory conditions, cannot be directly related to industrial conditions because of the change of scale of the device. Real situations are usually more complex, carrying new problems to solve.

A majority of real granular mixtures with which we have to deal in an industry, for example in a feed mixer, are multi-element heterogeneous systems. Particularly in this field the mixing processes have not been well mastered yet. According to the researches, so far, a significant impact on the course of the process is exerted by the proportions of mass or volumetric systems in the mixture (Boss, 1987). Furthermore, there are many parameters characteristic for the mixture, such as for example distribution of the size of the grains, shape, moisture content, coefficient of dynamic viscosity, angle of repose, or density, though it has been shown that only two parameters: the diameter of grains and density have a significant impact on the quality of the mixture after blending (Boss, 1987). Recognition of the principles governing the mixing process is one of significant scientific problems.

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The authors of the article have made an attempt to describe the course of the mixing process that was taking place in an industrial feed mixer with the use of cluster analysis. The cluster analysis is one of more important elements in multi-dimensional, statistical data analysis. In contemporary nomenclature the cluster analysis should be ranked as one of the taxonomic methods (Mezzich and Solomon, 1980). Cluster analysis is a set of methods serving to isolate homogeneous subpopulations among the items originating from a heterogeneous population (Tryon, 1939). The basic idea is to find groups (clusters) of items which are more alike (in the sense of the measure applied) to the items that form a part of a particular cluster (inside the group) rather than to items from other clusters (Tryon, 1939). The application of the cluster analysis is connected with taxonomical description of the items as well as with typology structure (classification with respect of similarity), data simplifying and its reduction, as well as with the search for hidden data (Brzeziński, 1987; Marek, 1989; Noworol, 1989; Richling, 1992).

Taxonomy, a science concerning the principles of ordering and classification of items, has its broad application in many fields of science, for example in the field of biology it includes a set of common and strictly applied principles of classification of animal and vegetable organisms as well as the principles of description of species, the way they are named, and the systematic units *ie* taxons, that they form. Among others, there is so-called taxonomy of Wrocław, which is recognized. The taxonomy of Wrocław is the method elaborated by mathematicians from Wrocław that enables grouping of items (soils, sites, *etc*.) on the basis of their similarity, taking into account many characteristics simultaneously. Among the grouping techniques we can distinguish element grouping (the simplest example here is the Czekanowski diagram), hierarchical grouping (the method of taxonomy of Wrocław) or the cluster analysis (among others factor analysis) (Richling, 1992).

The aim of the research was classification of the components that are included in multi-element granular mixture as well as finding similarity in the behaviour of grains during mixing, and evaluation of the impact of participation of particular elements on the course of the mixing process.

MATERIALS AND METHODS

The experiment was conducted in industrial conditions in the Ovigor Fodder Mixing Plant. For the purposes of the investigation, a temporal mixer with immovable chamber and vertical worm agitator was used. Dimensions of the feed mixer are given in Table 1, whereas the schematic drawing is presented in Fig. 1. The power of the mixer was 5.5 kW. The mixing velocity was constant throughout the course of mixing. The mass of the granular material charged to the mixer was 2000 kg. A mixture of feed for pigeons constituted a multi-element, heterogeneous granular structure. A demonstration picture of the examined mixture is presented in Fig. 2. The composition of the examined mixture is

T a b l e 1. Dimensions of the feed mixer used to carry out the research (Ovigor®)

Dimensions of the mixer	(mm)
Height of the cylindrical part – A	1550
Height of the conic part – B	1600
Height of the pour-out outlet – C	300
Internal diameter of the cylindrical part – D	1800
Internal diameter of the pour-out outlet – E	300

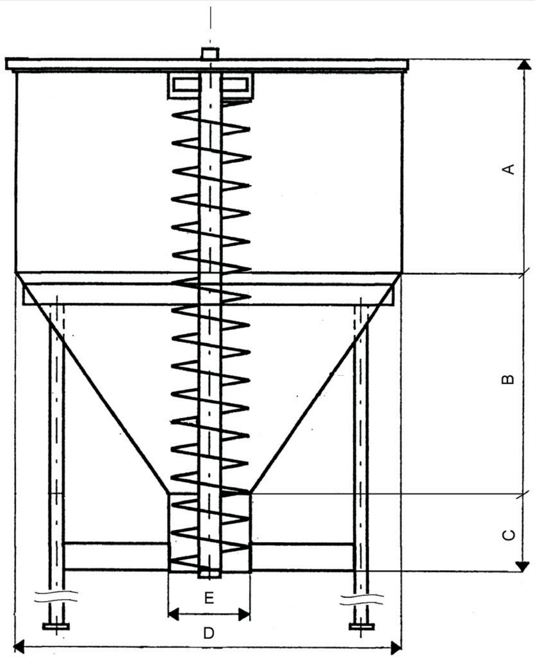

Fig. 1. Schematic of the feed mixer that was used to carry out the research, a temporal mixer with immovable chamber and a vertical worm agitator (Ovigor®).

Fig. 2. Demonstration picture of the examined granular mixture (elaborated by authors).

presented in Table 2. The static bulk density ρ_n was determined based on the PN-C-04532:1980 standard. The average size of grain was determined with the use of control screens in sieve analysis. The measuring procedure was based on the PN-C-04501:1971 standard. Table 3 gives the material properties: the grain diameter and bulk density. External recirculation of the mixed elements with the use of a bucket conveyor was characteristic for the process. Mixing of the charged granular material occurred as a result of the motion of the mixer worm agitator as well as a result of recirculation of elements through the bucket conveyor. The granular material charged to the mixer left the mixer through the mixer outlet and was directed toward the charging hopper and then it entered the mixer again through the bucket conveyor (Fig. 1). The humidity of components was not measured for the experiment, thus this factor was omitted in assessing the impact of mass fractions of multi-element granular structure on the mixing process. As mentioned above, humidity is not a significant factor of mixing. Moreover, the humidity of components is consistent with norms and must be controlled by an employee of the Ovigor Fodder Mixing Plant. The full cycle of mixing, from the moment of pouring all the elements into the mixer, lasted for 30 min. At the same time samples were being produced. The collection of samples was a discrete process and it occurred in the place of elements pouring out at time intervals of 30 s. In this way, 60 samples were obtained. Then, the samples were divided into particular elements. Each component was weighted and the mass of separated elements was expressed in percentage portions. In this way the percentage shares of particular elements of the mixture were obtained depending on the time of mixing (subsequent minutes). Selection of the place of sample taking seemed to be well justified as it was the end of the production process.

T a b l e 2. Composition of the examined granular mixture, percentage and mass shares on input (Ovigor®)

Components of the mixtures	Percent portion (%)	Mass portion (kg)
Dari (white sorghum)	1.25	25
Yellow pea	5.00	100
Barley	29.00	580
Maize	16.00	320
Field pea	10.00	200
Yellow millet	2.25	45
Wheat	30.00	600
Black sunflower	1.50	30
Sorghum	5.00	100
Total	100.00	2000

T a b l e 3. Characteristic properties of mixed granular materials (elaborated by authors)

Components of the mixtures	Bulk density (kg m^{-3})	Average size of particles (mm)
Dari	723	3.38
Yellow pea	771	6.95
Barley	605	3.32
Maize	726	8.16
Field pea	793	6.86
Yellow millet	732	2.26
Wheat	718	3.74
Black sunflower	430	4.90
Sorghum	697	3.94

Statistical analysis was carried out with the use of cluster analysis. On this basis, the classification of the components that are included in multi-element granular mixture as well as finding the similarity in the behaviour of grains during mixing were conducted. Additionally, evaluation of the impact of participation of particular elements on the course of the mixing process was made. Due to the application of the cluster analysis, similarity was found between the items in the set of output data and it was divided into subsets among which the similarity was the greatest. In order to carry out the aim of the research, the following algorithm was used:

1. Data matrix was defined.

The percentage portion of particular elements depending on the time of mixing (Table 4) constituted the output data matrix. The items of the matrix (the cases) were the components of the mixture, whereas the characteristics (variable) were the percentage shares of those components in subsequent minutes of mixing.

2. Standardization of variables was made.
3. Similarity measure was chosen.

The Euclidean measure of distances between items was applied.

4. The matrix of taxonomic distances was described (Table 5).
5. The agglomeration of clusters was carried out.

The aim of the agglomeration of clusters was to obtain a graph called dendrogram (Fig. 3). The agglomeration of clusters was carried out by use of a hierarchical method - the Ward method. The best effectiveness of this method is commonly confirmed. The characteristic of this method is the assurance of minimal variance within clusters. This method provides homogeneity inside the clusters and heterogeneity between them (in the sense of minimization and maximization of the variances) (Marek, 1989). The starting point in the Ward method is the matrix of distance. In the matrix, it is searched for the closest pair of clusters (items defined as particular elements). Then, the items are joined in

T a b l e 4. Percentage share of particular elements of the examined mixture depending on the time of mixing (elaborated by authors)

Item number	Components of the mixture	Percent portions during mixing											
		Time of mixing (min)											
		0.5	1	1.5	2	2.5	3	3.5	4	...	29	29.5	30
1	Maize	11.26	25.18	45.56	60.07	48.27	28.65	11.58	5.74	...	21.04	25.72	23.14
2	Field pea	13.97	10.53	3.49	1.67	2.44	2.42	5.03	9.72	...	9.91	8.79	8.21
3	Yellow pea	5.78	3.20	2.51	4.57	9.79	11.42	15.20	10.20	...	6.64	5.54	6.37
4	Sunflower	1.85	0.54	0.28	0.05	0.00	0.08	0.10	0.23	...	1.92	2.31	1.77
...		...	...	...	...	...	...	...	...	...	...	...	...
8	Sorghum	0.09	0.32	0.54	0.08	0.04	0.05	0.00	0.05	...	6.19	7.56	7.88
9	Millet	0.19	0.17	0.09	0.12	0.11	0.05	0.00	0.03	...	2.79	1.23	0.87

T a b l e 5. Matrix of Euclidean distances obtained for elements of the examined mixture (elaborated by authors)

Components of the mixture	Maize	Field pea	Yellow pea	Sunflower	Wheat	Barley	Dari	Sorghum	Millet	Minimal values
Maize	0	7.8309	8.9576	10.432	11.418	9.7268	10.041	9.3519	10.208	7.831
Field pea	7.8309	0	3.6582	4.6038	13.069	14.822	4.7849	4.5001	4.7687	3.658
Yellow pea	8.9576	3.6582	0	2.3053	15.786	16.465	1.8523	1.9541	2.5355	1.852
Sunflower	10.432	4.6038	2.3053	0	17.447	18.42	1.5192	3.0394	1.0004	1.000
Wheat	11.418	13.069	15.786	17.447	0	7.3074	17.236	16.168	17.491	7.307
Barley	9.7268	14.822	16.465	18.42	7.3074	0	17.851	16.626	18.312	7.307
Dari	10.041	4.7849	1.8523	1.5192	17.236	17.851	0	1.8531	1.8512	1.519
Sorghum	9.3519	4.5001	1.9541	3.0394	16.168	16.626	1.8531	0	3.2494	1.853
Millet	10.208	4.7687	2.5355	1.0004	17.491	18.312	1.8512	3.2494	0	1.000
									Mean	3.703
									Standard deviation σ	2.942
									Critical value W_k	9.588

one, new agglomerated cluster. The last step is the change of the matrix distance considering the newly formed cluster. The procedure of clustering should be carried out by sequences, reducing the matrix until there will be only one value characterizing the distance between clusters (Marek, 1989). The plan of the agglomeration course presents the structure as well as values of the taxonomic distances of neighbour joining for the separated clusters (Table 6). The results of the agglomeration are presented in Fig. 3.

6. The analysis of dendrogram was made.

While dividing the dendrogram into clusters, the analysis of fusion curve, presented in Fig. 4, was made. In the place where the fusion curve becomes flatter *ie* where the additional increase of information is not large by addition of subsequent items to the already existing group, we cut off the branches of the dendrogram. As the final criterion of the stoppage of the process of agglomeration and verification of the affiliation of the items (particular elements) to the dendrogram, the method proposed by Hellwig (1968) was used. In this method, two subsets are considered to be fundamentally different if the distance between a pair of points belonging to two different subsets is bigger than a certain critical value (W_k). In order to evaluate the critical value, a minimal value in particular rows of distance matrix (matrix of Euclidean distances) has to be found (Table 5). Then, for variables formed in this manner, arithmetic mean and standard deviation σ are calculated. The critical value is calculated on the basis of the following formula (Pluta, 1977):

$$W_k = \bar{x} + 2\sigma, \qquad (1)$$

where:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(x_1 - \bar{x})^2}{n}}, \qquad (2)$$

x_i – successive minimal values in the rows of Euclidean distances matrix, $\bar{x}$ – mean of minimal values, n – number of elements in matrix of Euclidean distances.

7. The analysis of each cluster was made.

By analysing every cluster, we can obtain information as to what characteristics were decisive in the formation of a particular cluster. In order to make the analysis, the method of arithmetic means was applied (Roseman and Donald, 1962). In this method for the output data, for the three clusters, the arithmetic means of subsequent characteristics Xn (the subsequent minutes of mixing) were calculated. The following step was to calculate a group average X, which is average for a particular characteristic (minutes of mixing). The structure indicator of each cluster are quotients Xn/X (Table 7). A quotient larger than 1.0 proves the domination of a particular characteristic in the cluster.

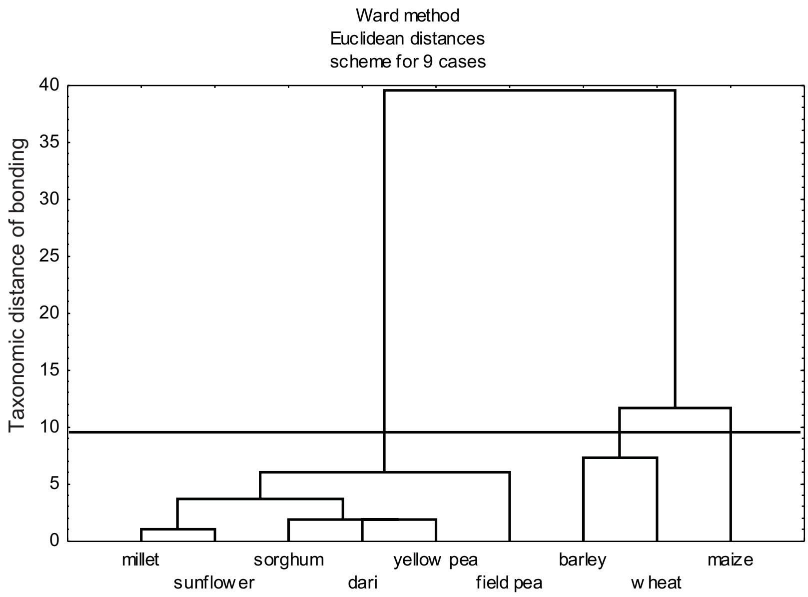

Fig. 3. Dendrogram illustrating the obtained cluster hierarchy of particular elements for the examined mixture (elaborated by authors).

T a b l e 6. Plan of the course of agglomeration obtained for the examined mixture (elaborated by authors)

Connections of agglomerate distances	Volume No.								
	1	2	3	4	5	6	7	8	9
1.000400	Sunflower	Millet							
1.852329	Yellow pea	Dari							
1.920709	Yellow pea	Dari	Sorghum						
3.690550	Yellow pea	Dari	Sorghum	Sunflower	Millet				
6.027926	Field pea	Yellow pea	Dari	Sorghum	Sunflower	Millet			
7.307390	Wheat	Barley							
11.66087	Maize	Wheat	Barley						
39.52712	Maize	Wheat	Barley	Field pea	Yellow pea	Dari	Sorghum	Sunflower	Millet

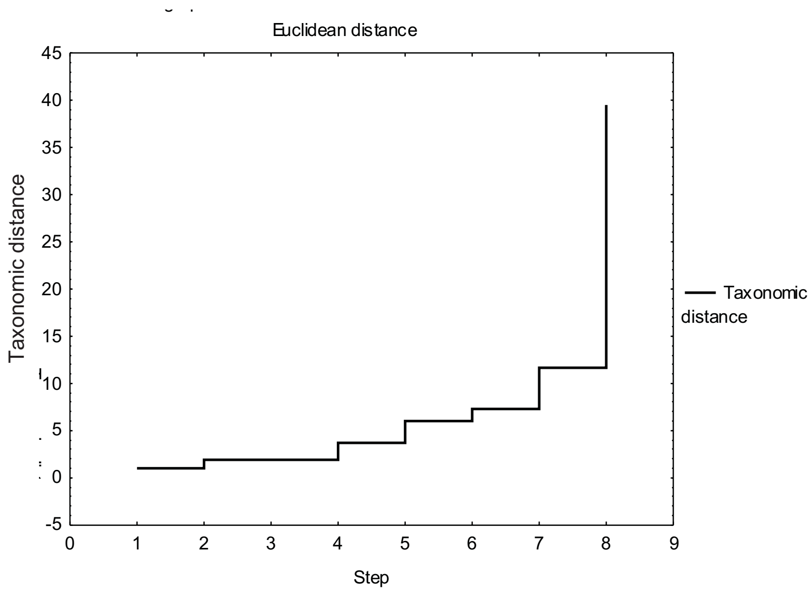

Fig. 4. Rate of increase of taxonomic distances for the elements of the examined mixture (elaborated by authors).

T a b l e 7. Particular cluster similarities assessment according to the properties (min) of Xn/X quotients values for the mixture (elaborated by authors)

Parameters	Mixing time (min)				
	0.5	1	…	29.5	30
		Cluster 1			
Yellow millet	0.190	0.170	…	1.230	0.870
Black sunflower	1.850	0.540	…	2.310	1.770
Sorghum	0.090	0.320	…	7.560	7.880
Dari	0.050	0.110	…	4.420	4.570
Yellow pea	5.780	3.200	…	5.540	6.370
Field pea	13.970	10.530	…	8.790	8.210
Mean X1	3.655	2.478	…	4.975	4.945
Mean X	13.110	11.591	…	15.133	15.053
X1/X	0.279	0.214	…	0.329	0.328
		Cluster 2			
Barley	37.240	29.530	…	45.220	46.190
Wheat	47.560	34.740	…	35.410	36.480
Mean X2	42.400	32.135	…	40.315	41.335
Mean X	13.110	11.591	…	15.133	15.053
X2/X	3.234	2.772	…	2.664	2.746
		Cluster 3			
Maize	11.260	25.180	…	25.720	23.140
Mean X3	11.260	25.180	…	25.720	23.140
Mean X	13.110	11.591	…	15.133	15.053
X3/X	0.859	2.172	…	1.700	1.537

RESULTS

Table 4 presents the results of experimental studies which served as the output data matrix in the algorithm of the cluster analysis.

The matrix of taxonomic distances which described the resemblance between the items is presented in Table 5. Whereas, the values of taxonomic distances of neighbour joining for separated clusters are presented in Table 6.

Another step for the analysis was to make agglomerations of the clusters in order to obtain a dendrogram (Fig. 3). The obtained dendrogram that illustrates the cluster hierarchy of particular elements was subject to analysis. In order to determine the number of clusters and particular elements of the mixture that belong to that mixture, the fusion curve presented in Fig. 4 was analysed and then the critical value W_k was calculated. The critical value, after being substituted to the Eq. (1), was tantamount to $W_k = 9.59$. The value was marked on the graph (Fig. 3) with a red line. The critical value divided the dendrogram into three clusters. The composition of the particular clusters is presented in Fig. 3 and Table 8.

The last step was to make an analysis of each of the separated clusters. By calculating quotients Xn/X (arithmetic mean of the subsequent clusters / group average) the domination of a particular characteristic (minute of mixing) in a cluster was determined. Graphical interpretation of the calculated quotients for particular minutes of mixing is presented in Fig. 5.

DISCUSSION

T a b l e 8. Division of mixture components into clusters (elaborated by authors)

Components of the mixture	Portion of a component in the mixture (%)	Bulk density (kg m^{-3})	Average size of particles (mm)
		Cluster 1	
Field pea	10.00	793	6.86
Yellow pea	5.00	771	6.95
Sorghum	5.00	697	3.94
Yellow millet	2.25	732	2.26
Black sunflower	1.50	430	4.90
Dari	1.25	723	3.38
		Cluster 2	
Barley	29.00	605	3.32
Wheat	30.00	718	3.74
		Cluster 3	
Maize	16.00	726	8.16

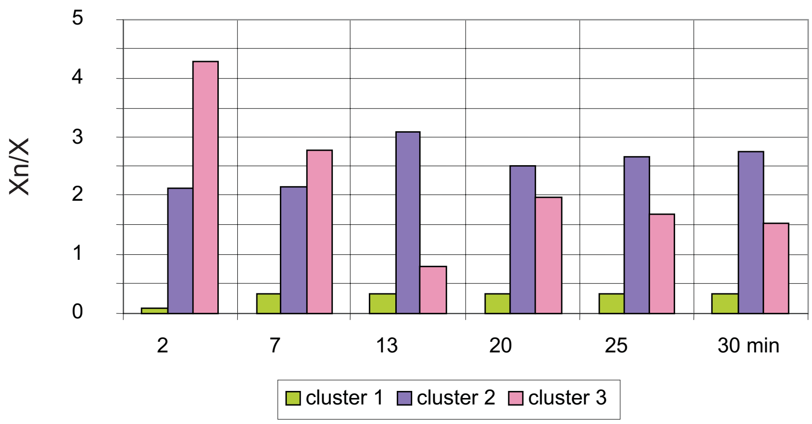

Fig. 5. Value of quotients Xn/X determined in 2, 7, 13, 20, 25 and 30 min of the process for the examined mixture (particular min). Quotient value bigger than 1 indicates domination of a particular cluster (elaborated by authors).

The analysis dividing the elements into 3 groups gave information about similar behaviour of particles of wheat and barley grains forming one cluster, and about similar behaviour of agglomerated grains in a cluster consisting of the grains of field peas, yellow peas, dari, sorghum, sunflower and millet. Maize was separated into a 1-element separate cluster.

While making the analysis of the particular mixture clusters (Fig. 5) it was observed that the biggest impact on the course of the process was that of two elements agglomerated in one cluster (barley and wheat); the two elements have the biggest percentage share among the elements in the mixture. Values of the quotients Xn/X of this cluster in 60 cases (30 min of the process) were larger than 1 and in 54 cases the quotient had the highest value (maximal) of the quotient Xn/X. The total portion of these elements in the mixture was 59%. These grains behaviour is similar, as they show similar values *ie* bulk density and grain sizes. The value of the quotient Xn/X of the one-element cluster, maize, with percentage share of 16, in 45 cases was larger than 1 and this cluster dominated in 6 cases. The behaviour of this grain during mixing with recirculation was individual and characteristic to such an extent that it was separated into one cluster. The separation of maize to a 1-element cluster may be additionally caused by the biggest size of the grains among all the elements of the mixture. The remaining elements *ie* field pea, yellow pea, dari, sorghum, sunflower and millet, with the smallest percentage share levels, did not have a significant impact on the course of the mixing process because the value of the quotient Xn/X in all those cases was smaller than 1.

CONCLUSIONS

1. The cluster analysis is a modern approach to mixing granular particles process description. Further on it constitutes a very useful instrument that allows the description of mechanisms of mixing multi-element, heterogeneous granular structures as well as allows us to understand the principles that govern such processes better.

2. The classification of the feed for pigeons mixture consisting of 9 different types of elements concerning their behaviour in the course of the process using an industrial mixer was made. The similarity in behaviour of wheat and barley grains was determined – these are the elements with similar bulk densities and grain dimensions.

3. The behaviour of maize grains that are of the largest size among all the elements of the mixture during mixing with recirculation was so individual and characteristic that the element was separated into a 1-element cluster.

4. The remaining elements (field pea, yellow pea, dari, sorghum, sunflower and millet) of varied bulk densities and component size were behaving similarly during mixing and that is why they were classified into one cluster.

5. The greatest impact on the course of the mixing process was that of wheat and barley; these grains had the biggest share in the mixture that amounted to 59%.

6. Maize also had a significant impact on the course of the process; its percentage share amounted to 16%.

7. The remaining elements did not have any significant impact on the course of the mixing process with recirculation of the elements.

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