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ANDRIUS LAUČKA

DEVELOPMENT OF A METHOD FOR MONITORING THE GRANULATION PROCESS OF INORGANIC FERTILIZERS

SUMMARY OF DOCTORAL DISSERTATION

TECHNOLOGICAL SCIENCES, ELECTRICAL AND ELECTRONICS ENGINEERING (T 001)

Kaunas
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KAUNAS UNIVERSITY OF TECHNOLOGY

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This doctoral dissertation was prepared at Kaunas University of Technology, Faculty of Electrical and Electronics Engineering, Department of Electronics Engineering during the period of 2015–2020. The studies were supported by Research Council of Lithuania.

Scientific Supervisor:
Prof. Dr. Darius ANDRIUKAITIS (Kaunas University of Technology, Technological Sciences, Electrical and Electronics Engineering – T 001).

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Prof. Dr. Vidas RAUDONIS (Kaunas University of Technology, Technological Sciences, Informatics Engineering, T 007).

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Address: K. Donelaičio St. 73-402, 44249 Kaunas, Lithuania.
Tel. no. (+370) 37 300 042; fax. (+370) 37 324 144; e-mail doktorantura@ktu.lt.

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ANDRIUS LAUČKA

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Mokslinis vadovas:
Prof. dr. Darius ANDRIUKAITIS (Kauno technologijos universitetas, technologijos mokslai, elektros ir elektronikos inžinerija, T 001).

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Prof. Habil. dr. Arūnas LUKOŠEVIČIUS (Kauno technologijos universitetas, technologijos mokslai, elektros ir elektronikos inžinerija, T 001);
Prof. dr. Jurij NOVICKIJ (Vilniaus Gedimino technikos universitetas, technologijos mokslai, elektros ir elektronikos inžinerija, T 001);
Prof. Habil. dr. Krzysztof OKARMA (Ščecino Vakarų Pamario techninių mokslų universitetas, Lenkija, technologijos mokslai, elektros ir elektronikos inžinerija, T 001);
Prof. dr. Vidas RAUDONIS (Kauno technologijos universitetas, technologijos mokslai, informatikos inžinerija, T 007).

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Adresas: K. Donelaičio g. 73-402, 44249 Kaunas, Lietuva.
Tel. (370) 37 300 042; faks. (370) 37 324 144; el. paštas doktorantura@ktu.lt.

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INTRODUCTION

Relevance of the problem

The increase of efficiency of cultivated land is negatively affected by pests and lack of nutrients. All nutrients contained in food products come from soil. Naturally, soil contains nitrogen, potassium, calcium and phosphorus [10]. These materials have an effect on the crop growth. When crop rotation is not carried out, fertile layer of ground loses its nutrients and has no time to recover. Therefore, fertilizers are widely used in farming, which when injected into soil, enhances the growth and development of plants [22].

The main chemical substances used in the production of fertilizers are usually in powder form. The chemical reactions used in manufacturing process allow to produce pellets. The fertilizer with equivalent properties must be selected when pellets of different substances are mixed. The shape and size of pellets are the features that affect the compatibility of chemical materials [5]. This allows to prevent segregation, and therefore, cultivated land is evenly fertilized with different substances. Fertilizers of poor composition (poor compatibility) are distributed unevenly across the soil and conditions the lack of specific microelements.

Friable particles are characterised by specific distribution according to their size. The measurement of pellet distribution is one of the most important measurements of development process for assuring the quality of production. The size and shape of fertiliser pellets are determined by the equipment used for the formation of pellets. Pellets that are shaped similarly to circle tend to be distributed more evenly and further apart when they are distributed by using fertiliser spreader in a field of cultivated land. The optimal results of fertilisation depend on three main factors: spreader, operator and properties of fertiliser pellets. These properties are (hardness, hygroscopicity, dustiness and other) created in the course of manufacturing process.

While falling down in drying tower, pellets collide with opposite air flow and crystallise, while residues of the melted mixture of chemical substances settle on the perforated plates that are gradually clogging them up. This leads to decreased production capacity, increased amount of fine fraction, increased dispersion of pellet diameter, quality parameters of production fall below the tolerance limit. After the identification of such changes, the equipment of inorganic fertiliser pellets must be washed by stopping the whole technological process. The currently used solution is periodic cleaning operations with respect to the experience of an operator and laboratory measurements of assessment of variation of pellet properties, which are time consuming because of required preparation and transportation of samples. The objective evaluation of clogging of equipment can be carried out by using a contactless measuring method. Because of the high efficiency of computer equipment, the method of digital image processing can be considered one of the most promising contactless pellet measuring methods. The processing of visual information provides a large amount of additional information about the production. This measuring method allows to save the image of every separate pellet and examine it later by using different image processing algorithm. More than 10 times faster measuring compared to the traditional direct measuring methods would allow to precisely determine early contamination, assure rational performance of equipment and minimise the amount of fine fraction.

The contactless measuring methods used in production monitoring allow the digitalisation of results. The synthesis of automation of measurement processes, big-data and methods of their analysis transfers the task of production assessment into the fourth resolution of industry. The pellet formation system lacks assessment feedback sub-system, instead of relying on the operator's experience. Therefore, the **scientific problem** is whether the monitoring of connection between the pellet parameters and parameters of their production line will assure the detection of contamination of production line in the early stage.

Scientific hypothesis

The scientific hypothesis presented in this dissertation states that monitoring of pellet formation process can be carried out by evaluating the connection between pellet form, size, distribution of composition of particles and parameters of the production line.

Object of study

This dissertation examines the contamination of fertiliser formation equipment during the technologic process. The parameters of fertiliser pellets and production line are examined in order to determine their relation to the contamination of production line. The studies were carried out to evaluate the information about the contamination of production line provided by the contactless measurements. The novelty of scientific studies is closely related to the evaluation of these parameters. The examined methods are used for the evaluation of pellet production and contactless monitoring. The verification of methods is carried out in the production line of inorganic fertilisers.

A new approach to the assessment of the volume of irregularly shaped pellets by using two-dimensional view is presented in this work. This view is closely dependant on the precision of segmentation, i.e., distribution into pellet objects. The conformity of results with results of control equipment is solved in the field of technical equipment and view processing. These goals are assigned to the task of view processing:

1) Scanning of particle in its characteristic position (regular outline of pellet);

2) Effect of pellet size on segmentation of view, by the assessment of precision of volume of pellet's object compared to the actual volume of pellet;
3) Conformity of results of granulometric composition with the results of control equipment.

The novelty of carried out pellet view analysis is related to a detailed processing of visual information. The consequent algorithm of pellet processing is determined by the assessment of geometric parameters of each pellet. The main part of such algorithm is a sum of volumes of layers of the object (layers equal to the height of 1 point of image).

Aim of the research

The aim of this dissertation is to create and examine a method for monitoring inorganic fertiliser formation equipment that allows to evaluate the parameters of pellet shape, size, granulometric composition and parameters of production line for the evaluation of contamination of its equipment.

These objectives were formulated to achieve the aim of the dissertation:

1. To examine the parameters of fertiliser pellets and indirect or contactless measuring methods;
2. To develop and verify contactless measuring method for describing parameters of pellets;
3. To propose and compile a model for describing the connection between fertiliser formation system parameters and the parameters of fertiliser pellet manufacturing process, which lead to the contamination of granulator with melted mixture;
4. To develop and examine the monitoring method for monitoring inorganic fertiliser formation process based on fuzzy logic, which would allow to make a reasonable decision concerning the stopping of the line at an early stage.

Scientific novelty

1. Contactless assessment model of the volume of irregularly shaped pellets on a plane was proposed in this work;
2. A model for describing the connection between the production of fertilisers and parameters of production line, which at the early stage evaluates the contamination of granulator with melted mixture;
3. Contactless method of monitoring of pellet formation process able to warn about the contamination level of equipment by evaluating the received measurement data was developed in the course of this work.

Methodology of study

The analysis of contactless and indirect methods of pellet measuring is presented in this work. Such methods are usually characterised by faster, more detailed and automatised measuring process. Since sieving method commonly used by fertiliser manufacturers is considered a benchmark, the results of the proposed method of evaluation of granulated production must conform to the results of control equipment.

In order to replace traditional measurements, alternative measuring method was analysed. Pellet models were formed for such evaluation in order to develop a measuring method based on the rational use of equipment. The use of contactless and indirect measurement models increases the frequency of measuring while eliminating human-factor from the assessment chain. Such measurements allow for continuous monitoring of the state of fertiliser pellet formation equipment. The application of statistical methods of evaluation of results allows for timely reaction to the cases of contamination.

Practical benefits of the research

The developed auxiliary system is suitable for use in the fertilizer pellet production factory under real production conditions. An operator can make objective decisions concerning the contamination of granulation system with melted mixture. The system allows precise identification of equipment cleaning at the early stage, ensuring maximum yield of quality products.

Approbation of results

Four scientific papers on this topic were announced in the Institute of Scientific Information (ISI) publications with citation indices. The results of dissertation were presented in 3 international conferences.

Structure of the dissertation

Doctoral dissertation consists of an introduction, four main chapters, conclusions, literature reference list and list of author's publications. The main part of the dissertation contains 110 pictures and description of 119 sources of cited literature.

The introductory chapter discusses the relevance of the problem, the scientific problem is formulated and solved, and the aim of work as well as objectives required to achieve it are formulated according to the scientific problem and presented hypothesis. This chapter as well provides information about the novelty of scientific study at the practical benefit of its results.

The first chapter of the dissertation provides an overview of literature sources. Various methods of pellet measuring are analysed. The advantages of indirect and contactless measurement methods over direct measurement methods are assessed. The method of processing digital images is defined as a method that provides most information about the production.

In the second chapter, the testing of pellet models by assessing their volume, using two-dimensional information, was presented. The measurements with irregular models are carried out and then used to create mathematical models of assessment of pellet's volume. The measurements by the assessment of data of several different camera views are carried out by determining the position of digital camera. These measurements are used to scan the characteristic view of the pellet.

The third chapter presents measuring results related to the determination of connection between clogging up of granule formation equipment, and their quantitative, qualitative parameters are presented. Unrelated parameters are rejected by assessing the changes in pellets size and quantity, while values that are related to changes are used for the conclusion of the fuzzy logic model.

The fourth chapter provides the assessment of connection between results received by using contactless measuring of pellets and contamination of granulation equipment. The reliability of the contamination identification type system based on fuzzy logic is evaluated. Such reliability facilitates the objective assessment of the state of contamination of the production line.

1. LITERATURE REVIEW

The techniques of pellet formation are reviewed in this work. During the granulation process, the particles are connected together by creating bonds between them. The components of fertilizers are turned into pellets by applying special binding substance (usually liquid state material). The product in pellet form has advantages over powdery form: easier to transport, allows to prevent product segregation.

The importance of fertilizer pellet size is related to ballistics: size and density of pellets determine how fast and how far they can be thrown by the fertilizer spreader. Long spreading distance does not always mean good results (highest yield). Equal distribution of fertilizer is more important, and it depends on the properties of fertilizer.

One of the most common methods of producing carbamide, ammonium nitrate (niter) fertilizers is based on cooling of product using airflow. Prilling is considered to be the best way of forming equal spherical particles from solutions and suspensions.

Prilling equipment, used for production, inevitably becomes clogged up, and it mainly depends on chemical components and additives of pellets. Short-term and long-term cleaning of equipment is necessary. Timely stopping of production line means less losses because of lower quantity of reprocessed production, less wasted energy producing low quality product and lower general contamination of equipment, when contamination is identified earlier.

As fertilizer production volumes in the chemical industry can be up to hundreds and even thousands of tonnes per hour, even a slight variation of parameters can lead to high losses of energy or low-quality production. Direct measurements carried out in local laboratories require lots of time; moreover, not all measuring methods allow to assess such physical parameters: shape, size and density of pellet.

Contactless measurement methods eliminate the shortcoming of direct measurement methods. Most commonly used contactless measuring methods: laser diffraction [4, 14, 26], acoustic spectroscopy [3, 16, 23], infrared spectroscopy [7], spatial filtering [6, 18], sedimentation methods [2], image analysis methods (in liquids) [13], using microscopes (Scanning Electron Microscope (SEM), Transmission Electron Microscopy (TEM)) [12], 3D measuring technique [9], analysis of pellet sample surface [11, 17], approximation of pellet particles [15, 21, 24, 25]).

The application of image processing technique to measuring pellet parameters not only reduces the time interval required for measuring, but also provides more information about the production. Such parameters as volume, roundness, symmetry, roughness, perimeter, area of pellet and other can be assessed. The studies on the relationship of these parameters with contamination of production equipment are carried out to assess the possibility of identifying contamination at an early stage.

2. IDENTIFICATION OF CONTAMINATION OF FERTILIZER PELLET PRILLING SYSTEM

In case of contamination pellet formation equipment, the amount of quality production is reduced, while the volumes of recycled production are increased. Unscheduled stopping of production line caused by changes in production process decreases the economic benefit for producers because of increased costs of recycling of low-quality production and supply of production for repeated pellet formation process. The production process of urea, ammonium nitrate (saltpetre) fertilizer is based on cooling of pellets using air. Prilling is considered to be the most effective way of producing identical spherical particles from solutions or suspensions. The process of formation of pellets takes place in prilling tower. The system of sieves positioned at the top part of the tower is one of the mains sections of the tower. The principle of operation of pellet formation equipment is based on braking down of sprayed material into drops according to the frequency of resonance induced by a resonator. The size of particles and their monodisperse distribution is corrected using sieves with differently sized holes. The scheme of pellet formation process is provided in fig. 2.1.

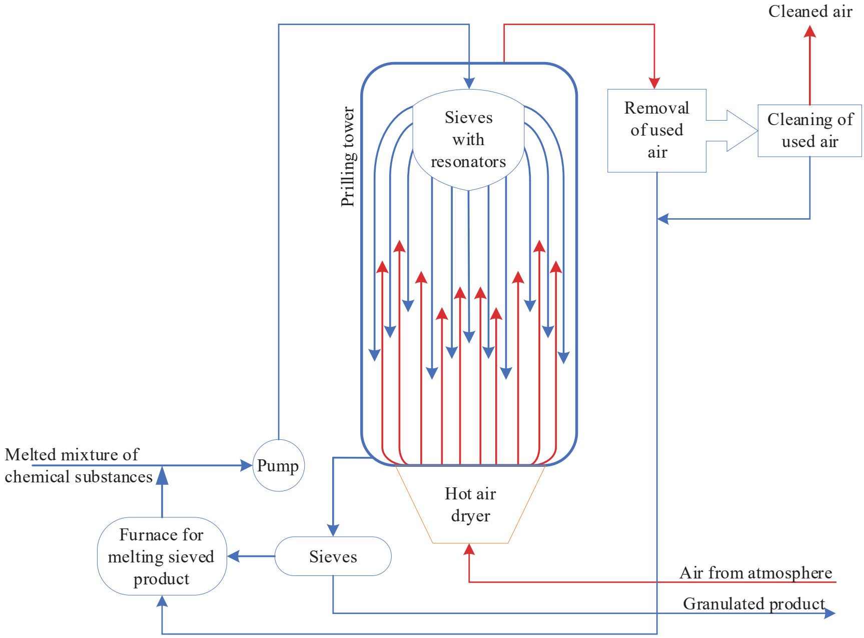

Figure 2.1. Process of pellet formation

During the prilling process, pellets are formed using the wet granulation method. First of all, after some chemical reactions, melted mixture is made from hard, liquid and gaseous substances. Depending on the additives that are used to change various properties of the product, such as better mechanical resistance, higher/lower hygroscopicity or other, melted mixture of different viscosity is made. Then, it is moved into the prilling tower where it causes problems of contamination of equipment.

When melted mixture settles on surfaces of sieves used in tower, the diameter of the holes of sieves reduces over time. When such conditions remain for a longer period of time, the amount of quality production is reduced. The average diameter of particles of final product becomes smaller. At the same time, the pellet size dispersion increases.

In the basic model of system level, when an operator notices a trend in the change of granulometric composition, an assumption is made that there is too much of the melted mixture in the system. It is as well a sign that perforated plates used in prilling process are contaminated, i.e., there is no effusion of mixture. In such case, the production process stops, and the cleaning of equipment is carried out.

After analysing the parameters of pellet formation process, the connection between the final product and state of contamination of equipment was determined by carrying out these measurements:

• Measuring of granulometric composition of product in a laboratory by using sieving method;

• Measuring of melted mixture feeding system vibrations damping.

In the first stage, the pellet size measurements were carried out in production plant laboratory using sieve shaker with 8 different hole diameter sieves [8]. The measurements were carried out regularly by taking samples from production lines using intervals of 1–2 hours. The relation between different data was assessed by examining few days of entries of the laboratory's journal (Fig. 2.2.).

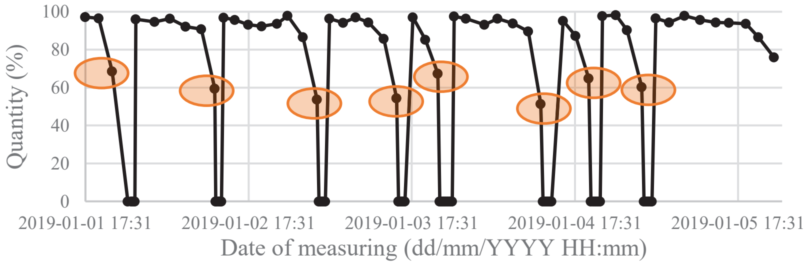

Figure 2.2. Measuring of quantity of production (ammonium nitrate) in one interval according to size [1–4] mm; equipment stopping time is indicated in orange colour

The results of granulometric composition measurements can be used for identifying the contamination of equipment. However, in order to evaluate system's state more reliably, the connection between different parameters was investigated.

Humidity and temperature measurements were carried out using non-invasive methods of measuring. Relative humidity of production was measured using near-infrared (NIR), temperature passive infrared (PIR) sensors. After the assessment of equipment and production parameters, the correlation between relative humidity, temperature and contamination of equipment was not found. Only seasonal variation of these parameters was noticed: relative humidity varies by about 0.21 % (must not exceed 0.30 %), while temperature varied within the range of 15–25 °C at the time of measuring, depending on the ambient temperature.

Production equipment performance was evaluated by analysing measurement data of vibration damping systems. The acceleration of system's vibrations was measured by installing an accelerometer (Bentley Nevada PN200150 [1]) in the intermediate section of system, which is used to supply prepared mixture of chemical substances to the prilling tower where the formation of pellets takes place. When a system is contaminated, the permeation of prepared melted mixture is reduced, which leads to the identification of system contamination (Fig. 2.3. provides results of measuring few days period in industrial fertilizer plant).

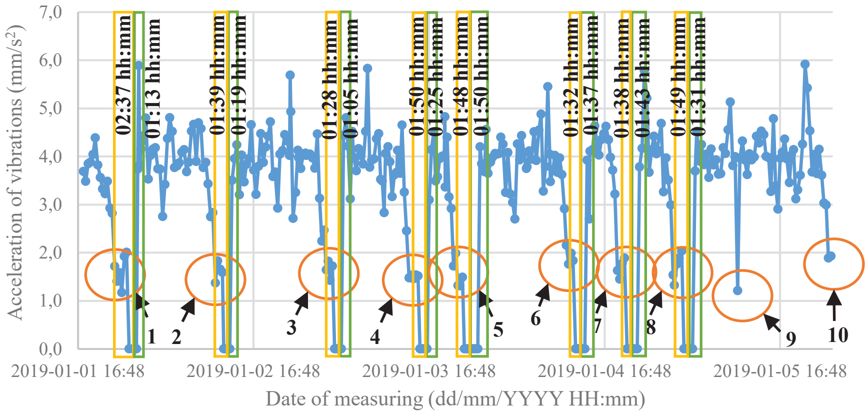

Figure 2.3. Results of vibration damping measurements; orange ellipses indicate the moments of system contamination, yellow marking – operation of equipment when contaminated, green marking – time of production line cleaning

The analysis of measuring results revealed that the operator is unable to precisely evaluate the state of the system and determine contamination in the early stage of the process. Fig. 2.3. graph provides measurements of system, which is working in contaminated state and where stopping of equipment is based on the operator's knowledge and experience. It is a subjective decision of evaluation of one of the parameters that describes the production process. According to these results, the production was going on for 1 h 48 min with the presence of contamination in the system.

With regard to the results of measurements of vibrations acceleration and factual stopping of the line, the decision about contamination of the production line was evaluated using statistical indicators of sensitivity and precision. After the assessment of the results from the graph Fig. 2.3., it was found that there were 3 cases of false determination out of 259 cases (false positive (FP)); 76 cases were identified as true positive (TP) (all cases are presented in Tab. 2.1.).

Table 2.1. Assessment of precision of contamination

		Gold standard	
		Contaminated	Uncontaminated
Test	Contaminated	76 (TP)	3 (FP)
	Uncontaminated	0 (FN)	259 (TN)

Sensitivity revealed the suitability of this method of diagnostics. The result of calculation of specificity revealed that this method is very specific and rarely presents false identification of contamination of pellet formation system.

The results were additionally evaluated with regard to the previous results of tests, connection between granulometric composition and the acceleration of vibrations (Fig. 2.4.).

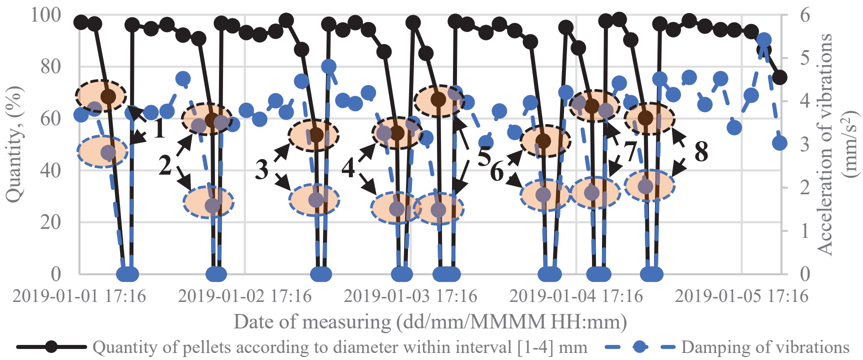

Figure 2.4. Results of vibration damping and granulometric composition of production; orange ellipses indicate contamination moments, i.e., variations of vibration damping and changes of pellet diameter

According to the received results, the operator's decision concerning system's contamination can be based not only on the measurements of vibration damping, but also on the measurements of pellet size variation. In this case, such decision is supported with additional information about the product. The results of different measurements allows preventing false evaluation of the system's state (*9* and *10* ellipses in Fig. 2.2.).

Fertilizer prilling equipment is a complex system of controlling chemical processes. An operator responsible for production parameters must understand chemical as well as technological processes of pellet formation. Therefore, operator's experience and competence directly affect production capacity and quality. An operator is in a crucial position of system's operation algorithm (Fig. 2.5.).

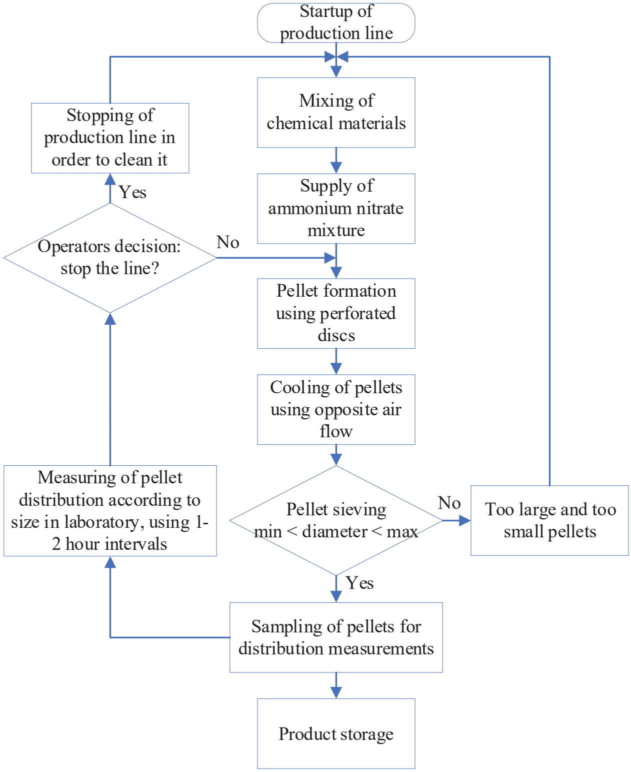

Figure 2.5. Current algorithm of control/operation of prilling system

An increase in quantity of smaller fraction ([0–1] mm diameter) pellets and decrease of larger ([1–4] mm diameter) have been noticed. After finding a connection between the results of measurements of different parameters, a fuzzy logic model was developed using these parameters:

- Pellets of [1–4] mm diameter > 97 %;
- Pellets of [0–1] mm diameter < 3 %;
- Average diameter of pellet $d_{50} \approx 2.8$ mm;
- Acceleration of vibrations in supply system > 3 mm/s^2.

The logic of contamination identification type model was concluded according to the experience gained by operators that take part in the production process and gathered measuring results. After systemising and describing all parameters using linguistic rules, the contamination identification type systems with 4 inputs and one output was developed. The value received at the output of fuzzy logic model (Fig. 2.6.) is a coefficient that describes system's contamination.

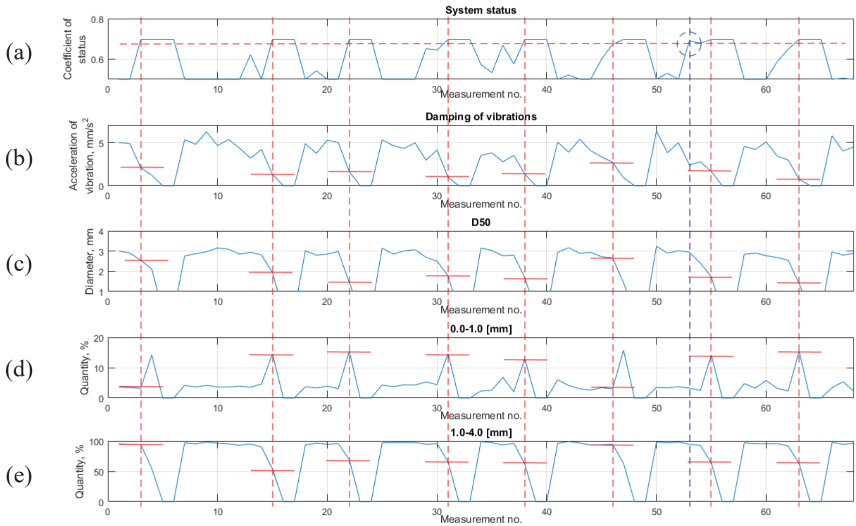

Figure 2.6. Assessment of the system's state: (a) variation of system's state assessment coefficient, (b) measurements of supply system vibration damping, (c) distribution curve of average size of pellet, (d) curve of quantity of pellets according to the size within the range of [0.0–1.0] mm, (e) curve of quantity of pellets according to the size within the range of [1.0–4.0] mm; the stages of system's contamination marked with red straight lines, blue – false decision in the system

Equipment contamination evaluation results describe the operation of the system. In Fig. 2.6. graph, the stops of system dedicated to washing that match with equipment washing times provided in producer's journals can be distinguished (marked with red dotted lines). However, in one of the cases of evaluating of production line's state, there was an error in fuzzy system. It happened because of the threshold value of the decision, which was set to 0.6784. In case of an error, the coefficient of system's state acquired value 0.6906. While contamination of the system identified at the coefficient value 0.6971.

The results received by using fuzzy logic model were compared to the results of the neuro fuzzy logic model. The model was trained by using data gathered in real production line. The generated neuro fuzzy logic model has 81 rules. This model, when compared to the previously assessed fuzzy logic model, falsely identified or failed to identify 4 cases of production line contamination (Fig. 2.7.). Large amounts of data required for training the neuro fuzzy logic model and worse results achieved while using it confirmed the assumption concerning the precision of the chosen model of fuzzy logic.

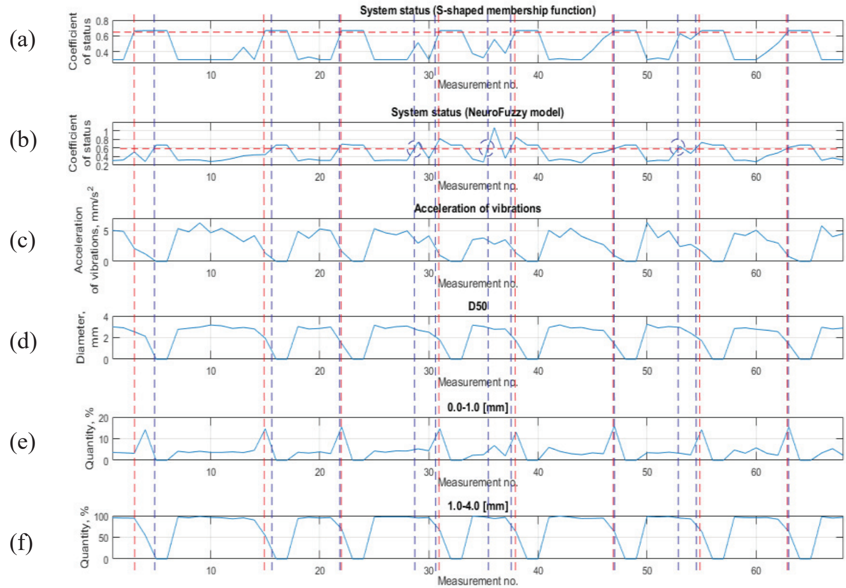

Figure 2.7. Assessment of the state of the system: (a) results received using fuzzy logic model, (b) results received using neuro fuzzy logic model, (c) measurements of acceleration of vibrations in supply system, (d) curve of distribution of average sized particles, (e) curve of pellet amount according to the size in interval [0.0–1.0], (f) curve of pellet amount according to the size in interval [1.0–4.0]; the stages of equipment contamination marked using red straight lines, blue – false decision of the system

The received results were evaluated according to the statistical indicators of sensitivity and precision. This allowed to compare the results with each other. The evaluation of precision of decision-making results is described in Tab. 2.2. Sensitivity revealed that the applied method is very sensitive and does not leave even one case of line contamination unidentified, while the result of specificity is worse than the value provided in the earlier calculations.

Table 2.2. Evaluation of precision of contamination 2

		Gold standard	
		Contaminated	Uncontaminated
Test	Contaminated	24 (TP)	1 (FP)
	Uncontaminated	0 (FN)	43 (TN)

The shortcoming of this system is related to the lack of direct measurements. The scarcity of planned measuring cannot assure the identification of production line contamination in its early stage. Therefore, because of its shortcomings, such system cannot replace the operator's position.

3. CONTACTLESS MEASUREMENT OF FERTILIZER PELLETS

Comprehensive examination of the product's composition is carried out in the laboratory. However, such detailed examinations of prepared sample require a lot of time. The measuring within 2–3 hour intervals is not a rational choice because of the duration. Since production capacity can be up to 50–150 tonnes per hour, every hour of production of products that does not meet the requirements means direct losses to the producer.

The assessment of pellets using screening method is based on mass measurement of different fractions of pellets. After measuring, the pellets left on different sieves are weighed and compared to the general mass of the sample. Their granulometric composition is determined in such way. Equivalent distribution of pellets using digital image processing technique is calculated by evaluating the volume of pellets (1)–(3):

$$\rho = \frac{m}{V}, \tag{1}$$

$$m = \rho \cdot V, \tag{2}$$

$$fraction = \frac{m_{sieve}}{m_{total}} = \frac{\rho \cdot V_{sieve}}{\rho \cdot V_{total}} = \frac{V_{sieve}}{V_{total}}, \tag{3}$$

where ρ is density [g/ml], m – mass [g], V – volume [ml], *fraction* – the number of granules in the corresponding diameter range in relation to the total amount of sample [%].

Sieves used for measuring pellets are not a rational choice, because such method allows measuring only two of three diameters of a pellet. Particle falls through sieve when two of its diagonal dimensions is smaller than the diameter of the sieve hole.

2D view of the pellets does not represent depth information, only two parameters can be obtained, i.e., height and width. When this method of contactless measurements is used, the precision of analysed distribution according to the volume depends on the level of conformity between used approximation model and real terrain of pellet's surface. Monoammonium phosphate was examined in this study.

The material that has been analysed does not feature a high level of roundness. It is categorized by more elongated shape. Therefore, most frequently used mathematical expression of the volume of ellipsoid does not conform with the real volume limited by the pellet. According to literature source [20], the reduction of error of measuring results is affected by dividing ellipsoid into layers, i.e., dividing its area into thin regions that are perpendicular to the longitudinal axis of the ellipse (Fig. 3.1.).

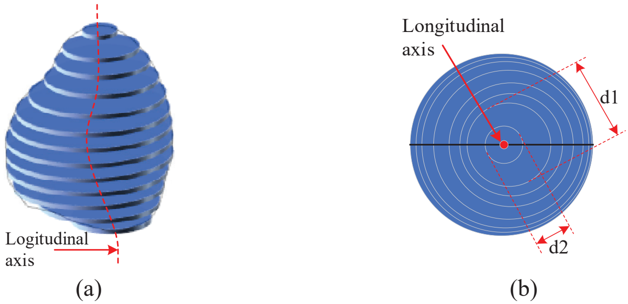

Figure 3.1. Division of the area limited by the pellet's contour into layers that are perpendicular to the pellet's longitudinal axis: (a) – 3D model of pellet divided into circle shaped layers, (b) – 3D model's view from above

Measuring method studied by authors Rashidi and Gholami [19] is based on a model of ideal ellipse, because ellipsoid consists of a sum of volumes of circles (4), (5):

$$V_i = S_i \,\Delta\, x, \tag{4}$$

$$V = \sum_{i=1}^{n} V_i \,, \tag{5}$$

where S_i is the area of circle limiting a layer; V_i – volume of the circle limiting the layer; V – volume limited by the ellipsoid.

According to the carried out measurements, most pellets are irregularly shaped; therefore, the convexity of the area limited by pellet was assessed to compensate for the calculation of volume. When pellets cut-out area is filled by convex shape, its depth can be rationally calculated using 2D view. The geometric shape of ellipse more precisely fills the pellet's cross section area (Fig. 3.2.).

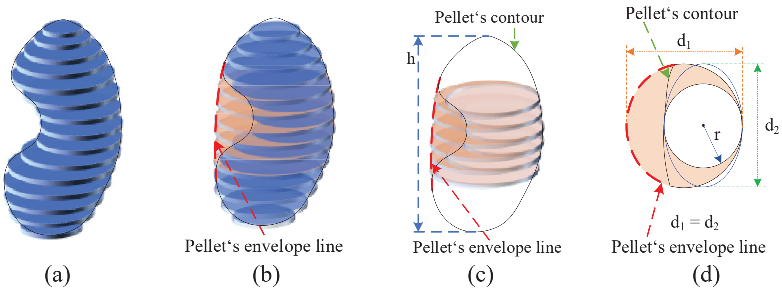

Figure 3.2. 3D model of irregularly shaped pellet: (a) – pellet's volume is composed of the sum of circle layers, (b) – regular shape of the pellet is limited by the pellet's envelope line, (c) – discrepancy between irregular volume and the volume limited by the envelope line, (d) – area of a cross section of pellet, limited by its envelope line

According to the pellet's model presented in Fig. 3.2., the cross section area limited by its envelope line is covered better by the geometric shape of an ellipse when compared to the shape of a circle. Both volumes of pellets are used for the calculation of volume, i.e., real and omitted area limited by the envelope line. After pellet is divided into the area equal to one point of an image and perpendicular to the pellet's longitudinal axis, the pellet's volume is calculated using integration (Fig. 3.2.) (6), (7):

$$S(h) = \pi r \frac{d_2}{2}, \tag{6}$$

$$V = \int_0^h S(h)dh, \tag{7}$$

where *S(h)* is the area of ellipse limiting the layer; *r* – half of a cross section of real area limited by the pellet; d_2 – diameter of cross section limited by the pellet's envelope line; *h* – length of the pellet, perpendicular to the planes of layers that limit it; *V* – volume limited by the pellet.

For testing the reliability of measuring method, evaluating irregularly shaped pellets, the models of plasticine were made. The general volume of the pellet is calculated using the method of sum of separate volumes of layers, whose height is equal to one point of the image. The results of measuring were compared to the data received using hydrostatic weighing method, which is considered to be a benchmark (Fig. 3.3.).

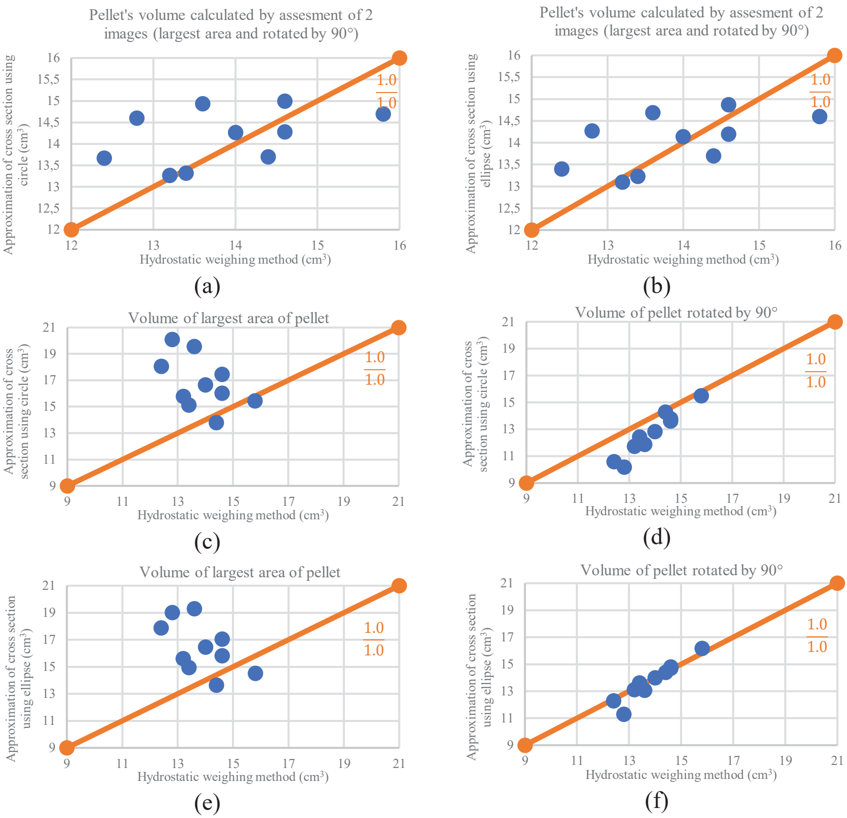

Figure 3.3. Measuring of volume of formed pellet model based on the contactless method of processing of digital images; all graphs present a comparison of results with the results received using hydrostatic weighing method of volume evaluation: (a) and (b) – cross-sections of pellet model layers approximated using 2 images (pellet scanned from two sides), (c) and (d) – one image, pellets approximated using circle, while (e) and (f) – also from one image but approximated using ellipse, (c) and (e) – largest area limited by the pellet scanned using camera, while (d) and (f) – pellet rotated by 90° from the previously mentioned position

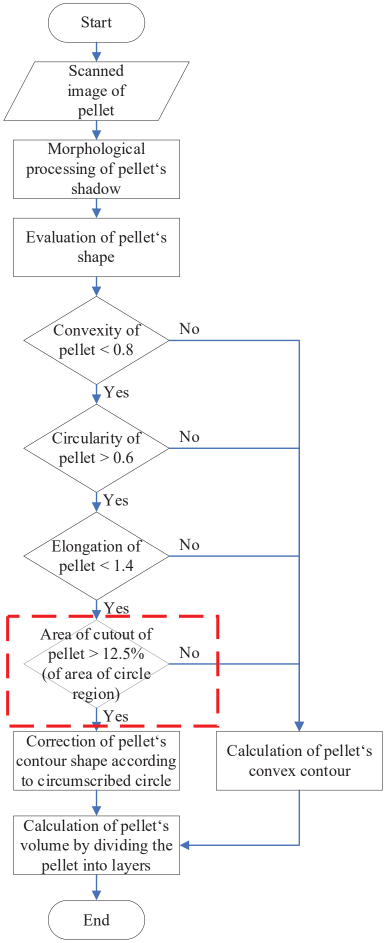

Figure 3.4. Algorithm of pellet shape evaluation

Mean absolute error when layers are approximated as circles is 1.191 cm^3 (when the pellet is evaluated rotated by 90° from the position in which pellet limits the largest possible area in relation to the field of view of the camera), which on average represents ~ 9 % of average volume of a pellet. Respectively, the root mean squared error is 1.38. While when the approximation of layers is carried out using ellipse geometric shape, MAE is 0.314 cm^3 (when evaluated pellet is rotated by 90° from the position in which pellet limits the largest possible area in relation to the field of view of the camera), and it represents ~ 2 % of average volume of the pellet.

The results of measurements carried out with regularly shaped pellets with cutouts showed that when the volume of separate layers is evaluated using a circle, MAE is up to 0.679 cm^3, while when using ellipse shape – 0.270 cm^3. Depending on the roundness, elongations and convexity of pellet shape, the pellets must be approximated using circle or ellipse. The threshold values of these evaluation criteria were determined during the examination. After evaluating the impact of pellet's cutout size on the shape of approximation, an algorithm for selecting approximation shape was created (Fig. 3.4.).

Mathematical model for recalculating the results of pellet volume evaluation using contactless measuring method was created in order to reduce the error of measuring. Mathematical model takes irregular shape of the pellet into account. When pellet's volume is calculated, the circularity of the region limited by the pellet's silhouette is additionally used. Data relation was noticed between missing evaluation of pellet's circularity and general determined pellet's volume. After application of the model (8), earlier results were recalculated (Fig. 3.5.):

$$V = \int_0^h S_{pellet}(h)dh \times \left(1 + \frac{1-C_{circle}}{10}\right), \quad (8)$$

where *S(h)* is the area of ellipse limiting the layer; *h* – length of the pellet, perpendicular to the planes of layers that limit it; C_{circle} – value of circularity of region limiting pellet's silhouette; S_{pellet} – area of the pellet's silhouette.

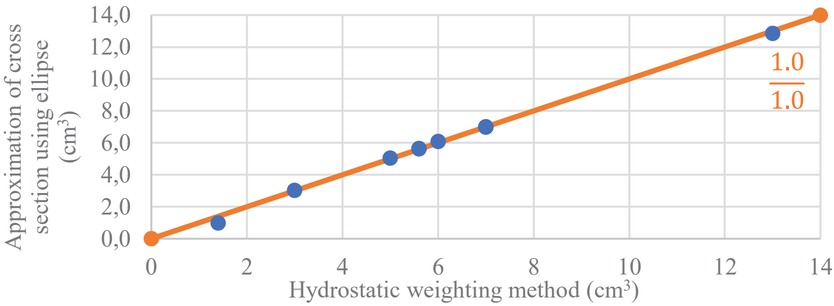

Figure 3.5. Recalculation of volume of pellet's model using the proposed mathematical model

After the application of proposed mathematical model, the relative error of received results was lower than 1.5 %. Since anisotropic shape is characteristic to the analysed material (monoammonium phosphate), the measurements are affected by the pellet's position in relation to the camera.

Pellets are evaluated according to their granulometric composition, which in laboratories of production plants is usually determined using measuring methods based on sieving. The same pellet sample was analysed using sieving technology and processing of digital images. MAE of measurements (Fig. 3.6.) is up to 4.0, while RMSE – 4.80.

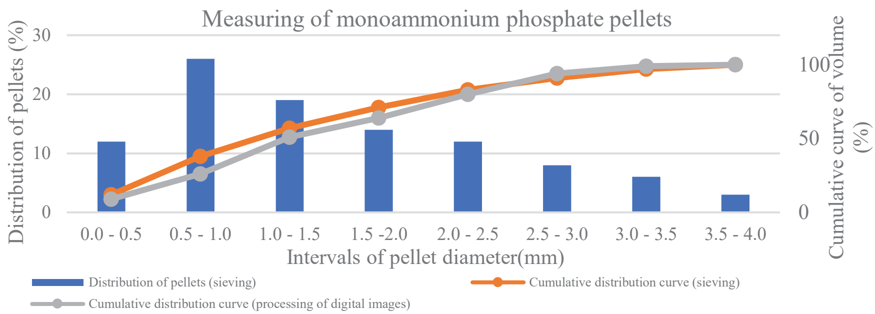

Figure 3.6. Results of measuring of pellet sample

Various methods are used for the adjustment of results received using digital processing of images (adjustment coefficients, mathematical models and other). Adjustment of cumulative curves (Fig. 3.7.) was carried out using the function of regression model. The results received after application of polynomial function were still dependent on the distribution of roundness of pellets.

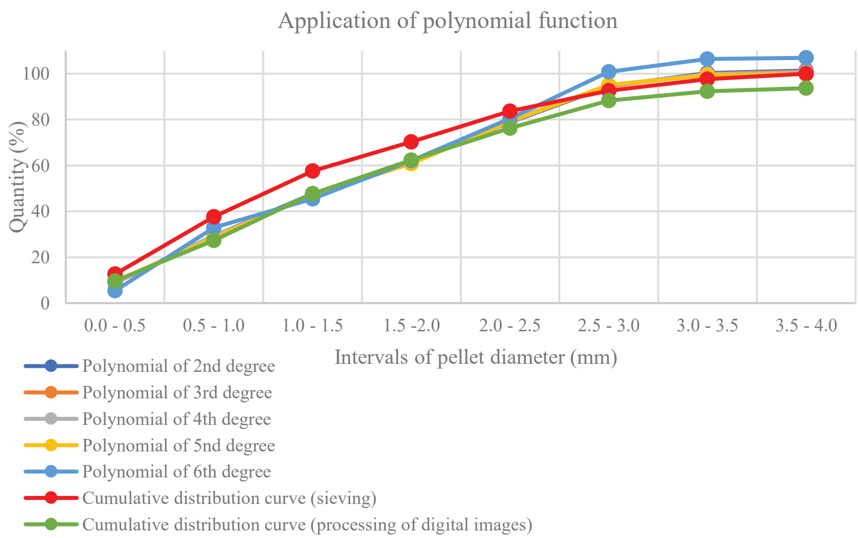

Figure 3.7. Recalculation of pellet sample by applying polynomial functions of different degree

The averages of the results of three measurements were used to determine polynomial roots. Polynomial function is not suitable for result adjustment because of very high variation of the analysed product's circularity coefficient distribution: varieties from 10.47 to 59.86 %.

Probability distributions were used for the adjustment of results. Models that allowed to achieve best prognosis results were compared during the experiment. The distribution of granulometric composition of analysed product was indicated most precisely by kernel distribution (not parametrical) and Birnbaum-Saunders distributions (Fig. 3.8.).

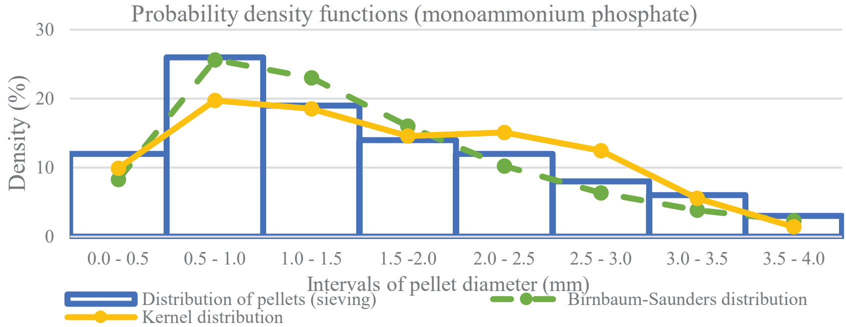

Figure 3.8. Calculation of pellet distribution according to their volume using processing of the digital images; recalculation of the results is carried out using probability distributions

Birnbaum-Saunders usage of probability distribution led to such results: MAE - 2.05 %, RMSE – 2.38 %. While application of kernel distribution resulted in: MAE – 2.38 %, RMSE – 3.08 %. For comparison, the used evaluation of pellet volume by applying the processing of digital images resulted in MAE – 4.00 %, RMSE – 4.80 %.

4. VERIFICATION OF PELLET FORMATION EQUIPMENT CONTAMINATION IDENTIFICATION MODEL

In case of production line contamination, the larger part of production is screened and supplied for reprocessing. However, not all production lines, especially older, have a possibility of returning the production for reprocessing. In this case, the production that does not meet quality requirements is supplied for the production of by-products.

During the measuring, pellet size was analysed using contactless measurement method, which made use of designed and installed pellet scanning equipment. The samples of fertilizers, automatically collected using the method of digital image processing, were analysed near the production line (Fig. 4.1.).

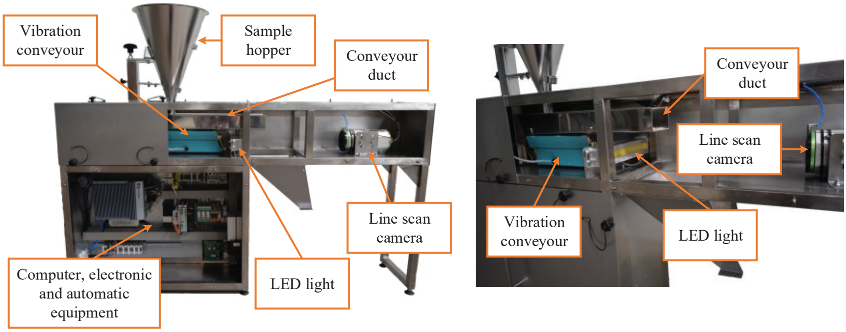

Figure 4.1. Experimental equipment of assessment of pellet granulometric composition in real production line

When using visual information for determining the distribution of pellets, minimum diameter of each sample particle was evaluated in order to determine its volume. Relative error received after comparing results with measurements based on sieving method is ≤ 10.21 % (quantity of pellets according to size interval [1–4] mm). The curve of measuring results was divided into 4 areas, according to state production process: regular production mode, contamination of equipment, cleaning of equipment and regular production mode (after cleaning operations). These periods are well illustrated by the graph of sieving method measuring results. The average of measurements from first period is up to 89.11 % (of pellet quantity), while the standard deviation is equal to 4.31 (Fig. 4.2.).

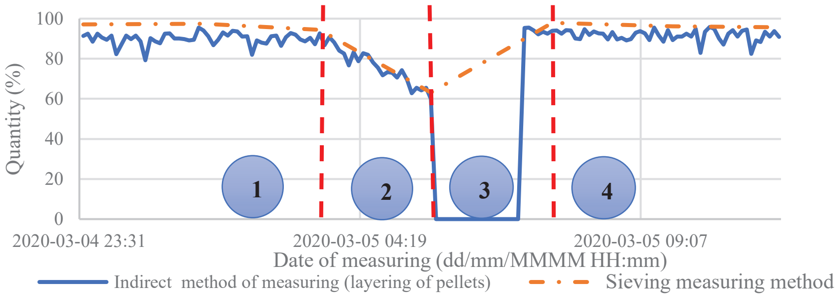

Figure 4.2. Measuring of pellets using contactless (processing of digital images) and sieving methods; the pellet layering method is used for the evaluation of their volume; the graph shows different states of production process

The average quantity of pellets in range [1–4] mm, according to their diameter is up to 89.97 %, while the standard error is 3.03 %. The standard error when equipment is operating before stopping (when equipment contamination process is more intensive) is up to 8.43, while after cleaning – 2.95. According to the modelling results of the 3rd chapter, the pellet volume evaluation model is best suited to be used with a characteristic view of pellet's shadow. This means that cut-out in pellets must be exposed in the field of view of the camera. Therefore, a vibration conveyor prototype was tested while conducting experiments with pellets of real product (Fig. 4.3.).

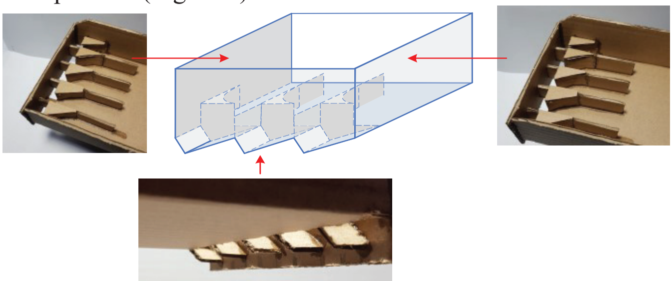

Figure 4.3. Prototype of conveyor duct was used for the evaluation of granulometric composition when the contactless measuring method was applied

Vibration conveyor duct prototype changed the position of the flow of the pellet sample in relation to the field of view of the digital camera. At the end of the duct, they are rotated by 90° in relation to the digital camera. Pellet volume evaluation method by layering using ellipses resulted in high conformity of results with results of control equipment: relative error was up to 4.45 %. After using a prototype of vibration conveyor duct, relative error was 1.75 %. The connection between pellet parameters and melted mixture supply system vibration damping was evaluated using this method of pellet measuring (Fig. 4.4.).

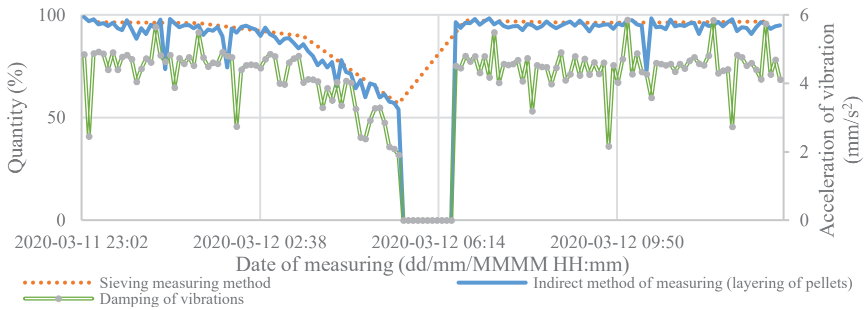

Figure 4.4. The evaluation of granulometric composition (quantity of pellets, according to diameter interval [1–4] mm) using direct and contactless measuring methods

According to the received results, high conformity of results was received using contactless measuring of granulometric composition with direct measurement results. The relative error of granulometric composition measurements is ≤ 1.83 %. A higher discrepancy of results is noticed when low quality production is analysed. The relation of data between the results of contactless granulometric composition and equipment vibration damping allows to replace the direct measurements.

When fuzzy logic decision-making model is presented with data of supply system vibration damping, granulometric composition of production, pellets quantity and other clear data, in the course of fuzzification process, clear input values are transformed into linguistic form of variables. Fuzzy sets were formed for each input according to the used function of dependence. A block structure of the contamination identification system is presented in Fig. 4.5.

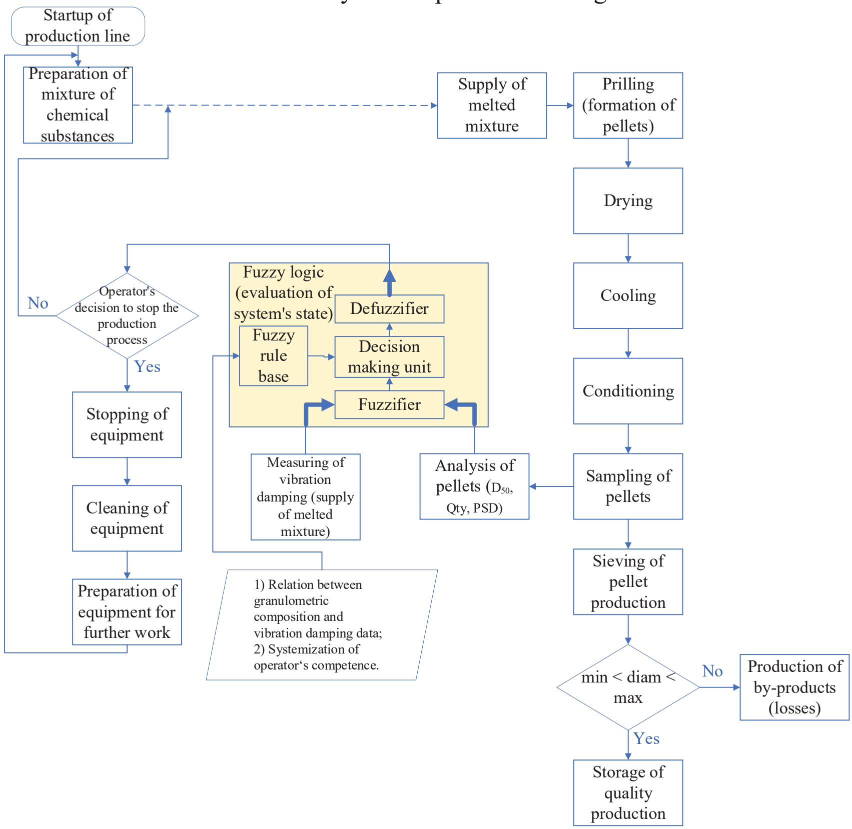

Figure 4.5. A block structure of the contamination identification system with fuzzy logic

The data of contactless measurements of granulometric composition provided for the model are evaluated according to the systemized observation of the operator, which are then used to conclude linguistic rules according to:

- Variation of quantity of pellets of different fractions;
- Variation of pellet size;

- Variation of pellet quantity;
- Variation of pellet shape (elongation);
- Increase of quantity of low-quality product.

After describing all of this and concluding base of fuzzy logic Mamdami type linguist rules, the experimental examinations were carried out. Received solution, as well as the type of system's rules, is a function of dependence of linguistic variables. The calculation of clear result solution is carried out using the most common method of centre of mass from Mamdami system. The level of contamination of the system is evaluated as the centre of mass of fuzzy set dependence function. The sets of fuzzy logic are described by S shaped reaction curve. The allowable values for the pellet granulometric composition are presented in Tab. 4.1.

Table 4.1. Allowable boundaries of granulometric composition

Sieve interval, mm	Minimum quantity of pellets, %	Maximum quantity of pellets, %
0.0–0.5	0.0	0.5
0.5–1.0	0.0	2.0
1.0–1.5	3.0	7.0
1.5–2.0	15.0	20.0
2.0–2.5	20.0	30.0
2.5–3.0	30.0	45.0
3.0–3.5	3.0	7.0
3.5–4.0	0.0	2.0

The fuzzy logic system with 19 inputs and 1 output is used for the realization of contamination identification type system. The state of the system is assessed using linguistic rules. The fuzzy logic system presented in previous chapter had only 8 linguistic rules for sieving method used for measuring pellets. The contactless measuring method allows a more detailed examining of production and provides a wider assortment of analysed parameters. During the analysis of collected empiric data, the relation of parameters of monitored process to quantitative parameters of pellets was determined. The tendency of particles gradually becoming smaller is a characteristic sign of contamination of the production line. A larger number of assessed parameters reduced the possibility of random error. The wider scope of analysis is used for the correction of linguistic rules of fuzzy logic. The system's contamination assessment coefficient was formed as an output value for the depiction of system's contamination. In regular working mode, its clue varies around 0.5. The value of coefficient increases with the increasing level of contamination. This numerical parameter allows to make an assumption about the contamination in the early stage. The equipment assessment data of two days were presented in Fig. 4.6. The installed equipment constantly gathers data. The data from more than a half year was analysed before beginning the experiments.

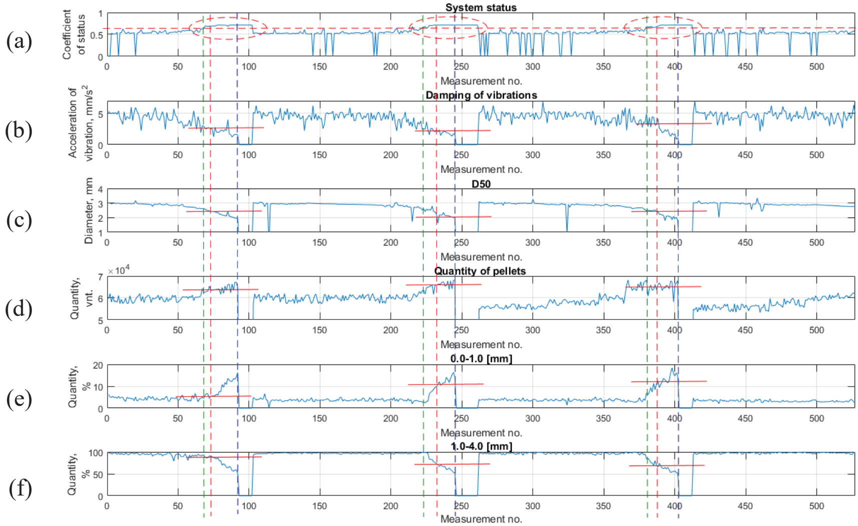

Figure 4.6. Assessment of state of system's contamination: (a) change of coefficient of system's state evaluation, (b) measurements of supply system vibration damping, (c) curve of distribution of average sized pellets, (d) variation of pellet quantity during production, (e) curve of variation of pellet diameter according to the size within [0–1] mm, (f) curve of variation of pellet diameter according to the size within [1–4] mm

The used method identified the changes of equipment's working mode. The green line in Fig. 4.6. graph indicates likely possible beginning of system's contamination. In order to make the final decision, the results of few last measurements are evaluated, because it helps to prevent false decision error (in Fig. 4.6. graph, red dotted line marks the identification of contamination by fuzzy logic systems, while blue marks the stopping of equipment based on the operator's decision). This allows to confirm the assumption about the detection of contamination in the early stage.

According to the results of these measurements, the overall working time of the line, when contamination is present, is 1 hour 22 minutes, while the time of cleaning is up to 54 minutes. In order to evaluate the advantage of this system more precisely, longer-term surveillance was carried out (Fig. 4.7. provides results of 10 days of surveillance).

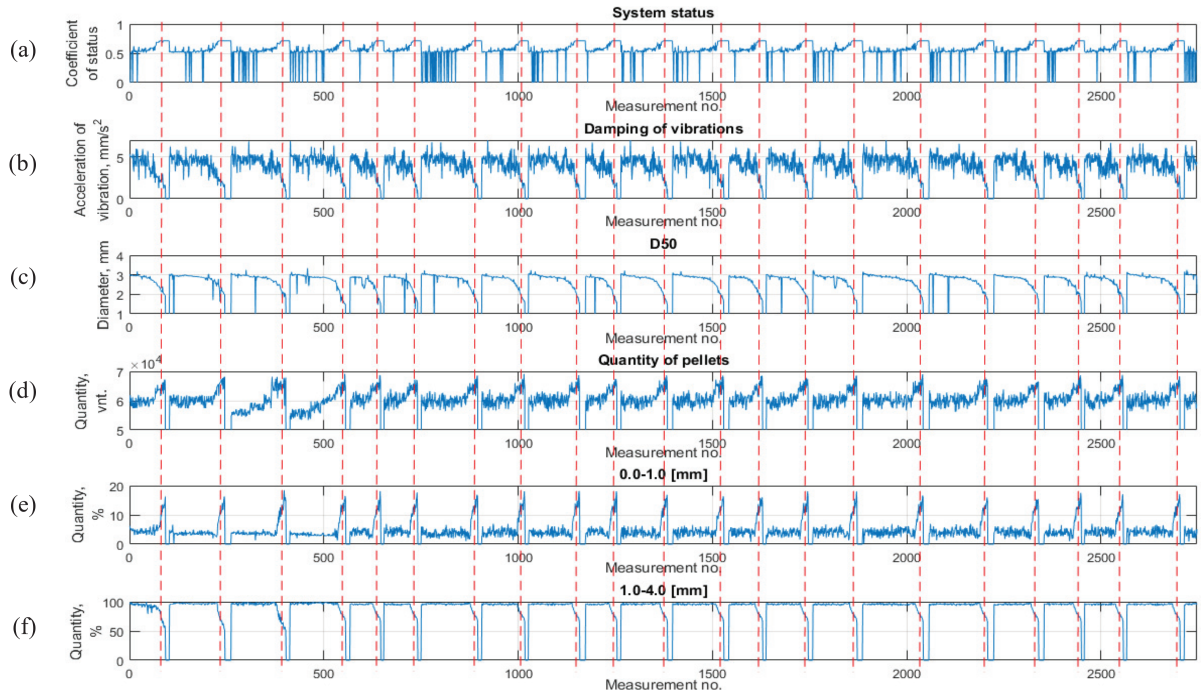

Figure 4.7. Surveillance and evaluation of production line during the time period of 10 days: (a) change of coefficient of system's state evaluation, (b) measurements of supply system vibration damping, (c) curve of distribution of average sized pellets, (d) variation of pellet quantity during production, (e) curve of variation of pellet diameter according to size within [0–1] mm, (f) curve of variation of the pellet diameter according to size within [1–4] mm; red colour indicates identified contamination of line (using fuzzy logic)

According to the assessment of results, it can be stated that the system of fuzzy logic allows to identify the contamination of line in its early stages. The production process can be stopped for about 57 minutes, because the changes of production parameters have been noticed at that stage. This leads to the current reduction of quantity of production sent to be stored, i.e., increasingly larger part of production is sieved because it does not meet the qualitative parameters of granulometric composition. After changes have been identified by the system, the quantity of high-quality production decreases from 83 % to 63 % at the time of stopping the line (after 57 minutes on average).

After evaluating that average capacity of fertilizer production line is 65 tones/hour, the losses incurred by a producer in 10 days are more than 450 tones. This amount can increase even further when part of the system's cleaning operations is evaluated as production losses, because the longer duration of exploitation of contaminated equipment leads to higher level of contamination. This leads to more preparation work for recovery of the production line to its regular working condition.

5. CONCLUSIONS

1. Balanced fertilization of plants is assured maintaining even the shape of the pellets, which assures better aerodynamic qualities. One of the crucial factors determining this is the contamination of pellet formation equipment, which leads to gradual decrease of the size of the particles. The identification of contamination of equipment at early stages allows to decrease the amount of production that needs to be sent for reprocessing. Contact sieving measuring method results in longer duration of production analysis when compared to the contactless methods. These measuring methods as well take into account a wider spectrum of production parameters. The correlation of results of the digital image processing method with the parameters of the production line can assure the identification of equipment contamination at the early stages, therefore, reduce the economic losses.
2. It has been determined that the data of granulometric composition, d_{50} and acceleration of vibrations of melted pellet mixture supply system are related. With changes of granulometric composition, when particles are becoming smaller, the intensity of vibrations of supply systems is as well becoming lower. When d_{50} of pellets is reduced by more than 30 % and the acceleration of vibrations is reduced by more than 50 % from the start of the productions, the contamination of the production line can be identified. The systems of assessment of state of production line based on the fuzzy logic allowed to evaluate the contamination of the system. However, because of the applied contact measuring, the applied method did not allow for the identification of contamination at the early stages.

3. When two-dimensional image analysis was used for the assessment of pellet volume, < 1.5 % relative error was achieved. Area limited by the pellet's contour is separated into layers which volume is integrated according to the roundness of the pellet. After the assessment of the position of the pellet scanning, it has been determined that when two video cameras are used, depending on the position of cameras in relation to each-other, up to 5 % relative measuring error is observed. This error is reduced when 90° angle between the cameras is formed. When a special model of sample transportation tray is used, the pellet flow position in relation to the field of view of the camera is altered and the relative error is reduced to 2 %. In order to make the results of contactless measuring match the "golden standard" sieving results used by the manufacturers, mathematical models were used for the correction of cumulative curves. The best results were achieved using Birnbaum-Saunders distribution: MAE - 1.64 %, RMSE - 2.00 %.
4. It has been found that when contamination is not present, the standard deviation of granulometric composition of fertilizers was ≤ 3.03 %, but it reached 10.31 % with contaminated equipment. However, it resulted in 4.45 % relative error. After using the proposed vibrational conveyor duct solution, relative error was reduced to 1.75 %. After applying the proposed measuring method, the pellet amount was additionally assessed. An increase of pellet amount indicates the contamination of the systems because of production particles becoming smaller. The linguistic rules of fuzzy logic created according to the systemised experience of operator and statistical results of production monitoring were verified by evaluating the connection between surfaces of different inlets.
5. The method of identification of line contamination was tested in real production environment. A wider spectrum allowed for the characterization of connection between parameters of production and production line. According to that, the database of linguistic rules of the systems was expanded up to 19 inputs, which reduced the possibility of false decision. All stops of the production line were identified during the verification of the system. The applied fuzzy logic model identified the contamination of the line 57 minutes before stopping of the line initiated by the operators. Such timely stopping of the line not only reduces the duration of cleaning of equipment, but also the losses incurred by the manufacturer. After 10-day analysis of production line, it was assessed that this system is able to reduce the losses by 450 tones.

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Curriculum Vitae

Academic background

Institution:	Years	Qualification/degree
Kaunas University of Technology	2015–2020	Doctoral studies in Interactive Electronic Systems
Kaunas University of Technology	2013–2015	Master in Electronics Engineering
Kaunas University of Technology	2009–2013	Bachelor in Electronics Engineering

Contact information: andrius.laucka@ktu.edu
Scientific interests: image processing, machine learning, computer vision systems.

REZIUMĖ

Problemos aktualumas

Dirbamos žemės efektyvumo didinimui neigiamos įtakos turi kenkėjai ir maistinių medžiagų trūkumas. Būtent visos maiste esančios maistinės medžiagos yra kilusios iš dirvožemio. Natūraliai dirvožemyje yra azoto, kalio, kalcio ir fosforo [1]. Pastarieji komponentai daro įtaką pasėlių augimui. Dirbant be sėjomainos, derlingas žemės sluoksnis praranda maistines medžiagas ir nespėja atsinaujinti. Todėl žemės ūkyje plačiai naudojamos trąšos, kurios, įterptos į dirvą, gerina augalų augimą ir vystymąsi [2].

Trąšų gamybos procese naudojamos pagrindinės cheminės medžiagos dažniausiai yra miltelių pavidalo. Vykdant chemines reakcijas, gamybos proceso metu formuojamos granulės. Maišant skirtingų medžiagų granules, svarbu parinkti trąšas su ekvivalenčiomis savybėmis. Būtent cheminių medžiagų suderinamumas lemia granulių formą ir dydį [3]. Tai padeda išvengti trąšų granulių išsisluoksniavimo, ir dirbamas laukas tolygiai patręšiamas skirtingomis medžiagomis.

Trąšų barstymo barstytuvais kokybės svarba smarkiai išauga, kai barstomos trąšos iš anksto apipurškiamos herbicidais. Tiek geometrinės savybės, tiek granulių masės pasiskirstymas turi didelę įtaką barstymo procesui naudojant net ir tikslius centrifuginius barstytuvus. Siekiamybė, kad trąšos būtų užduotų matmenų.

Birioms dalelėms būdingas tam tikras pasiskirstymas pagal dydį. Trąšų granulių pasiskirstymo matavimas jų gamybos procese yra vienas svarbiausių matavimų, susijusių su produkcijos kokybe. Trąšų granulių dydis ir forma priklauso nuo naudojamos granulių formavimo įrangos. Artimos apskritimo formai granulės tolygiau ir didesniu nuotoliu pasiskirsto išsviedžiamos barstytuvo dirbamos žemės lauke. Optimalus tręšimo rezultatas priklauso nuo trijų pagrindinių faktorių – barstytuvo, operatoriaus ir trąšų granulių savybių. Pastarosios savybės (kietumas, higroskopiškumas, dulkėtumas ir kt.) suteikiamos gamybos proceso metu.

Gamybos proceso metu krisdamos priliavimo bokšte, dalelės susiduria su priešpriešiniu oro srautu ir kristalizuojasi, o cheminių medžiagų lydalo likučiai nusėda ant perforuotų plokščių, palaipsniui jas užnešdami. Tai lemia padidėjusį smulkios frakcijos kiekį, sumažėjusias gamybos apimtis, didėja granulių diametro dispersija, produkcijos kokybiniai parametrai nukrenta žemiau tolerancijos ribos. Tai identifikavus, neorganinių trąšų granulių įranga yra plaunama, stabdant visą technologinį procesą. Šiuo metu taikomas sprendimas – periodinis įrangos plovimas atsižvelgiant į operatoriaus patirtį ir atliekamų granulių parametrų kitimo vertinimo laboratorinius matavimus, kurie, deja, yra imlūs laikui dėl mėginių paruošimo, jų transportavimo. Objektyviai spręsti apie sistemos užteršimą būtų galima taikant bekontaktį matavimo metodą. Didelė kompiuterinės įrangos sparta skaitmeninių vaizdų apdorojimo metodą leidžia laikyti vienu iš perspektyviausių bekontakčių dalelių matavimo būdų. Vaizdinės informacijos apdorojimas suteikia didelį kiekį papildomos informacijos apie produkciją. Taikant šį matavimo būdą, išsaugojamas kiekvienos atskiros dalelės vaizdas, kuris bet kada vėliau gali būti analizuojamas pagal skirtingą vaizdo apdorojimo algoritmą. Iki keliolikos kartų greičiau atliekami matavimai, palyginti su tradiciniais tiesioginiais matavimo metodais, leistų matavimo procese užtikrinti ir nustatyti ankstyvąjį užsiteršimą, užtikrinti racionalų įrangos našumą, maksimaliai sumažinti trąšų smulkios frakcijos kiekį.

Gamybos stebėsenoje taikomi bekontakčiai matavimo metodai leidžia skaitmenizuoti rezultatus. Matavimų automatizavimo, didžiųjų duomenų ir jų analizės metodų sintezė granuliuotos produkcijos vertinimo uždavinį perkelia į ketvirtąją pramonės rezoliuciją. Granulių formavimo sistema neturi grįžtamojo ryšio vertinimo posistemės, o remiamasi operatoriaus patirtimi. Todėl kyla **mokslinė problema** – ar granulių ir jų gamybinės linijos parametrų ryšio stebėsena leis užtikrinti linijos užteršimo aptikimą ankstyvoje stadijoje?

Mokslinė hipotezė

Disertacijoje iškelta mokslinė hipotezė, kad trąšų formavimo proceso stebėsena gali būti atliekama įvertinant ryšį tarp granulių formos, dydžio, dalelių pasiskirstymo sudėties ir gamybinės linijos parametrų.

Tyrimų objektas

Disertaciniame darbe nagrinėjamas trąšų formavimo įrangos užteršimas technologinio proceso metu. Tiriami trąšų granulių ir gamybinės linijos parametrai, siekiant nustatyti ryšį su linijos užteršimu. Atliekami tyrimai vertinant bekontakčių matavimų grįžtamąjį ryšį apie linijos būseną. Mokslinių tyrimų naujumas glaudžiai susijęs su šių parametrų ryšio vertinimu. Nagrinėjami metodai taikomi granulių gamybai vertinti ir bekontaktei stebėsenai. Metodų verifikavimas atliekamas neorganinių trąšų gamybos linijoje.

Darbo tikslas

Daktaro disertacijos tikslas – sukurti ir ištirti neorganinių trąšų formavimo įrangos stebėsenos metodą, vertinantį granulių formos, dydžio, granuliometrinės sudėties ir gamybinės linijos parametrus jos įrangos užteršimui nustatyti.

Darbo tikslui pasiekti suformuluoti uždaviniai:

1. Apžvelgti trąšų granulių parametrus ir netiesioginius ar bekontakčius jų matavimo būdus;
2. Sukurti ir patikrinti granulių parametrams nusakyti skirtą bekontakčių matavimų metodą;

3. Pasiūlyti ir sudaryti modelį trąšų formavimo sistemos parametrų ryšiui nusakyti su trąšų granulių gamybos proceso parametrais, lemiančiais granuliatorių užteršimą lydalu;
4. Sukurti ir ištirti neorganinių trąšų formavimo proceso stebėsenos metodą, besiremiantį neraiškiąja logika, kuris leidžia ankstyvoje stadijoje priimti pagrįstą sprendimą dėl linijos stabdymo.

Mokslinis darbo naujumas

1. Darbe pasiūlytas bekontaktis netaisyklingos formos granulių tūrio plokštumoje vertinimo modelis;
2. Sudarytas modelis ryšiui tarp trąšų produkcijos ir gamybos linijos parametrų nusakyti, kuris įvertina granuliatorių užteršimą lydalu ankstyvoje stadijoje;
3. Darbo metu buvo sukurtas ir ištirtas granulių formavimo proceso bekontaktis stebėjimo metodas, kuris, vertindamas gaunamus matavimų duomenis, perspėja apie įrangos užteršimo lygį.

Tyrimų metodika

Darbe pristatoma bekontakčių ir netiesioginių granulių matavimo metodų analizė. Pastarieji metodai paprastai pasižymi spartesniu, detalesniu ir automatizuotu matavimo atlikimu. Kadangi įprastai trąšų gamintojų naudojamas sijojimo metodas yra laikomas etaloniniu, todėl siūlomo granuliuotos produkcijos vertinimo metodo rezultatai privalo sutapti su kontrolinės įrangos rezultatais.

Siekiant pakeisti tradicinius matavimus, buvo analizuojami alternatyvūs matavimo metodai. Tam vertinti suformuoti granulių modeliai, siekiant sukurti racionaliu įrangos naudojimu pagrįstą matavimo metodą. Bekontakčių ir netiesioginių matavimo metodų taikymas padidina matavimų atlikimo dažnį, eliminuojant žmogiškąjį faktorių iš matavimo ir vertinimo grandinės. Tokie matavimai leidžia nuosekliai sekti trąšų granulių formavimo įrangos būklę. Taikant statistinius rezultatų vertinimo metodus, galima laiku reaguoti į įrangos užteršimo atvejus.

Praktinė darbo nauda

Sukurta pagalbinė sistema gali būti naudojama trąšų granulių gamybos fabrike realiomis gamybos sąlygomis. Operatorius gali priimti objektyvius sprendimus apie granuliavimo sistemos užteršimą lydalu. Sistema leidžia tiksliai identifikuoti įrangos plovimus ankstyvoje stadijoje, užtikrinant maksimalią kokybiškos produkcijos išeigą.

IŠVADOS

1. Subalansuotas augalų tręšimas užtikrinamas turint tolygią dalelių formą, kuri lemia geresnes aerodinamines jos savybes. Vienas kritinių tai lemiančių veiksnių – granulių formavimo įrangos sietų užsinešimas, kuris nulemia produkcijos smulkėjimą. Trąšų produkcijos gamintojams įrangos užteršimo identifikavimas ankstyvoje stadijoje leidžia sumažinti perdirbamos produkcijos apimtis. Kontaktinis sijojimo matavimo būdas lemia ilgesnę analizuojamos produkcijos trukmę, palyginti su bekontakčiais būdais. Taip pat šie matavimo būdai vertina platesnį produkcijos parametrų spektrą. Skaitmeninių vaizdų apdorojimo metodo rezultatų koreliacija su gamybinės linijos parametrais gali užtikrinti įrangos užteršimo identifikavimą dar ankstyvoje stadijoje, taip sumažinant patiriamus ekonominius nuostolius.
2. Buvo nustatyta, kad granuliometrinės sudėties, d_{50} ir granulių lydalo padavimo sistemos vibracijų pagreičio duomenys yra susiję tarpusavyje. Kintant granuliometrinei sudėčiai, kai dalelės smulkėja, kartu mažėja padavimo sistemos vibracijos. Granulių d_{50} sumažėjus daugiau kaip 30 %, o vibracijų pagreičiui sumažėjus daugiau kaip 50 % nuo gamybos pradžios, galima identifikuoti gamybinės linijos užteršimą. Neraiškiąja logika paremta gamybinės linijos būsenos vertinimo sistema leido įvertinti įrangos užteršimą. Tačiau naudojamas metodas neleido įrangos užteršimo identifikuoti ankstyvoje stadijoje dėl naudojamų kontaktinių matavimų.
3. Granulių tūriui vertinti naudojant dvimačio skaitmeninio vaizdo analizę, buvo pasiekta < 1,5 % santykinė paklaida. Granulės kontūro ribojamas plotas skaidomas sluoksniais, kurių tūris integruojamas atsižvelgiant į granulės apskritumą. Vertinant dalelių nuskaitymo poziciją nustatyta, kad, naudojant dvi vaizdo kameras, priklausomai nuo jų tarpusavio padėties, gaunama iki 5 % siekianti santykinė matavimo paklaida. Ši paklaida sumažėja kameroms tarpusavyje sudarant 90° kampą. O, panaudojus specialų granulių mėginio transportavimo lovelio maketą, yra pakeičiama dalelių srauto pozicija kameros regos lauko atžvilgiu, taip santykinę paklaidą sumažinant iki 2 %. Siekiant bekontakčio matavimo rezultatus sutapdinti su gamintojų naudojamu „auksinio standarto“ sijojimo rezultatu, buvo pritaikyti matematiniai modeliai kumuliacinėms kreivėms koreguoti. Geriausių rezultatų pasiekta naudojant Birnbaumo ir Saunderso skirstinį: MAE – 1,64 %, RMSE – 2,00 %.
4. Nustatyta, kad, kai nebuvo užteršimo, granuliometrinės trąšų sudėties standartinis nuokrypis buvo ≤ 3,03 %, o įrangos užteršimo atveju pasiekė net 10,31 %. Tačiau tai lėmė 4,45 % santykinę paklaidą. Panaudojus pasiūlytą vibrokonvejerio latako sprendimą, santykinė matavimų paklaida sumažėjo iki 1,75 %. Pritaikius pasiūlytą matavimo metodą, papildomai buvo įvertintas ir granulių kiekis, kurio didėjimas praneša apie sistemos užteršimą dėl smulkėjančios produkcijos. Pagal susistemintą operatorių patirtį ir statistinius

produkcijos stebėjimo rezultatus sudarytos neraiškiosios logikos lingvistinės taisyklės buvo patikrintos įvertinus ryšį tarp skirtingų įėjimų paviršių.

5. Realioje gamybinėje aplinkoje patikrintas linijos užteršimo identifikavimo metodas. Platesnis analizuojamų parametrų spektras leido charakterizuoti produkcijos ir gamybinės linijos parametrų ryšį. Pagal tai sistemos lingvistinių taisyklių bazė, praplėsta iki 19 įėjimų, sumažino neteisingo spendimo priėmimo galimybę. Atliekant sistemos verifikavimą, buvo identifikuoti visi linijos stabdymai. Pritaikytas neraiškiosios logikos modelis linijos užteršimą identifikavo likus vidutiniškai 57 minutėmis iki operatorių atliekamo linijos stabdymo. Toks savalaikis linijos stabdymas ne tik sutrumpina įrangos valymo trukmę dėl mažesnio užteršimo, bet ir sumažina gamintojo patiriamus nuostolius. Atlikus 10 parų gamybinės linijos parametrų analizę, buvo įvertinta, kad ši sistema gali iki 450 tonų sumažinti patiriamus nuostolius.

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Išleido Kauno technologijos universitetas, K. Donelaičio g. 73, 44249 Kaunas
Spausdino leidyklos „Technologija“ spaustuvė, Studentų g. 54, 51424 Kaunas