

Article

Operation Optimization of a Bucket Conveyor Transporting Wastes in the Processing Plant of a Hard Coal Mine

Sebastian Jendrysik ^{1,*}, Joanna Rogala-Rojek ¹, Daniel Kowol ¹ and Andrzej N. Wiczorek ²

¹ KOMAG Institute of Mining Technology, Pszczyńska 37, 44-100 Gliwice, Poland; jrogala@komag.eu (J.R.-R.); dkowol@komag.eu (D.K.)

² Faculty of Mining, Safety Engineering and Industrial Automation, Akademicka 2A, 44-100 Gliwice, Poland; andrzej.n.wiczorek@polsl.pl

* Correspondence: sjendrysik@komag.eu

Abstract: This study presents the structure and principles of operation of the control system for a bucket conveyor operating in a jig preparation plant. The idea of controlling the conveyor speed is to maintain constant, nominal filling of the buckets, and thus achieve a constant mass of material on the conveyor. As part of the completed task, a new control algorithm was developed and implemented to increase transport efficiency. Simulation and industrial test results were analyzed, in which the traditional PID controller was replaced with a fuzzy controller, which enabled control error reduction, thus achieving better control quality.

Keywords: coal mine; preparation plant; automation; bucket conveyor; control



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1. Introduction

Growing requirements from investors in the mining and processing industry, especially regarding its efficiency and effectiveness, have contributed to the development and design of technology to transport raw mining materials using bucket conveyors [1]. After achieving the required system reliability, the attention of designers and users focuses primarily on reducing operating costs by implementing advanced control and driving systems solutions. The developed solutions are intended, on the one hand, to reduce electricity consumption and, on the other hand, to extend the life of the conveyors.

In hard coal processing plants, bucket conveyors are used to transport and dewater materials in the beneficiation process in water pulsating jigs. In these situations, where the coal feed to be enriched has a small amount of waste product and/or semi-finished products, the conveyors operate for long times with low loads. Reducing the speed in such situations will not only reduce electricity consumption, but will also slow down wear of the conveyor. Less mechanical wear is observed when the conveyor operates at higher loads and lower speeds [2,3]. Bucket conveyor maintenance costs, which include the costs of replacing wearing parts as well as energy consumption costs by the electric motor, make it necessary to automate the operation of these devices and adapt their efficiency appropriately to the current demand [4]. A conveyor control system is presented, which is controlled by an automatic control system with a Smith predictor. This research presents a method for optimizing this algorithm using a fuzzy controller. These activities are part of the trend of using fuzzy logic controllers in the control systems of machines operating in jig beneficiation nodes.

2. Design and Characteristics of Bucket Conveyor Operation

Bucket conveyors are devices designed to transport bulk materials at large slope angles, such as coal, ores, aggregates, as well as crops and agricultural products such as cereal grains, sugar, etc. In the mining industry, they are used in preparation plants for transporting and dewatering materials in the beneficiation process in water pulsation jigs.

They are classified as multi-member cable conveyors. The members are buckets that are attached to cables, i.e., tapes or chains. Due to high loads in the mining industry, chain conveyors are mainly used. An example of a “KOMAG”-type bucket conveyor is shown in Figures 1 and A1.

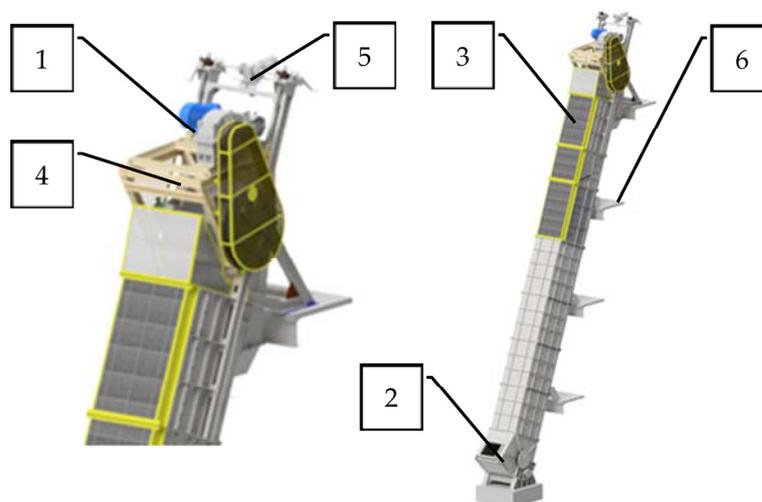


Figure 1. Diagram of the “Komag” bucket conveyor: 1—drive, 2—loading zone, 3—chain with buckets, 4—dumping zone, 5—tension station, 6—prop.

The conveyor drive consists of an electric motor and a mechanical transmission gear mounted on a sliding frame relative to the supporting structure installed on the upper end member. The drive shaft and chain stars are installed on bearings on the supporting structure, and are coupled with a mechanical gear via a chain transmission.

The tensioning device consists of tensioning screws and a worm gear driven by an electric motor. In addition, the device is equipped with a manual or automatic driving system, which allows controlling the chain tension within the return end station in the case of a motor failure.

During operation of the jig node (Figure 2), there are frequent changes in the flow rate of the material directed to the beneficiation process, and in the gravimetric composition of the beneficiated material changes; this, in turn, causes changes in load to the bucket conveyor. The speed of the conveyor should be adapted to the current load, and must be controlled in such a way as to prevent excessive accumulation of material in the loading zone of the conveyor, which may lead to conveyor stoppage, and thus stopping the entire jig node [5]. Since the beneficiation process in pulsation jigs takes place in a water environment (bucket conveyors are flooded with water to approximately half of their height), it is difficult to identify the degree of filling of the buckets within the conveyor return station (bucket loading zone), which complicates the automatic control process [6].

The output of the bucket conveyor can be controlled by changing its speed. A change in the motor speed translates into a change in the linear speed of the buckets transporting the material, which contributes to the amount of material transported at a given moment. The lower the speed, the greater the load to the conveyor buckets. When controlling the speed, the aim is to achieve a situation in which the nominal filling of the buckets is constant and, therefore, the instantaneous weight of the material on the conveyor is constant.

Changes in the intensity of the bottom product stream from the jig directed to the conveyor are the basic disturbances that affect the load to the conveyor, i.e., the mass of the material transported on the conveyor [7,8]. These changes result from the controlling action securing the constant height of the waste product layer in the jig compartment. These disturbances are identified by measuring the opening degree of the jig’s discharge flap. The control system must take into account delays resulting from the need to transport material from the jig to the feeding area of the conveyor.



Figure 2. Jig node: 1—bucket conveyor, 2—jig 1 (3 compartments), 3—jig 2 (3 compartments).

3. The Conveyor Speed Control System with Fuzzy Controller

The method developed at KOMAG for controlling the speed of the bucket conveyor operating in the beneficiation unit is based on predictive control using the information about the opening degree of the jig's discharge flap [9,10]. The KOMAG Institute of Mining Technology was established in shaping work safety in hard coal mines.

Traditional control systems with feedback adjust their operation depending on changes in the system's output. In predictive control, the controller adjusts its operation in advance before changes to the system's output occur, based on the object's behavior model [11].

The suggested solution assumes that the weight of the material transported on the conveyor depends on the conveyor speed and the degree of opening of the jig's discharge flap, through which the bottom product feeds the conveyor escapes. This assumption is true when the jig operates in a steady state, and feed is fed to the jig. In addition, the bottom product, discharged from the jig, falls into the water environment, covering several meters to the conveyor feeding zone. The time needed to cover this distance should be taken into account in the control system in the form of appropriate delays.

During operation of the jig node, due to the variable nature of the jig material removal process, the load to the bucket conveyor varies. The algorithm controlling the operation of the conveyor should actively correct the conveyor speed, striving to maintain the instantaneous mass of the transported material at a constant level. This mass is determined by analyzing the electric power consumed by the conveyor drive. It was assumed that in a short time the resistance to movement is constant, so changes in electrical power are caused by changes in the mass of the material transported in the conveyor buckets. The relationship between the power consumed by the conveyor motor and the mass of the transported material is described by the following equation [12]:

$$m = \frac{\Delta P \cdot \eta}{(\mu \cdot g \cdot \cos \alpha + g \cdot \sin \alpha) \cdot v} \quad [\text{kg}] \quad (1)$$

where its terms are defined as follows:

m —mass of transported material [kg],

ΔP —difference in power drawn from the power grid when operating with load and without load [W],

v —linear speed of buckets [m/s],

α —angle of inclination of the bucket conveyor ($\alpha = 60^\circ$),
 g —acceleration due to gravity ($g = 9.81\text{m/s}$),
 μ —resistance of movement ($\mu = 0.2$),
 η —motor efficiency ($\eta = 0.81$).

Bucket conveyors used in jig centers are characterized by sudden changes in power, which result from the mechanical structure of these conveyors, in particular, the presence of chain transmissions (Figure 3).

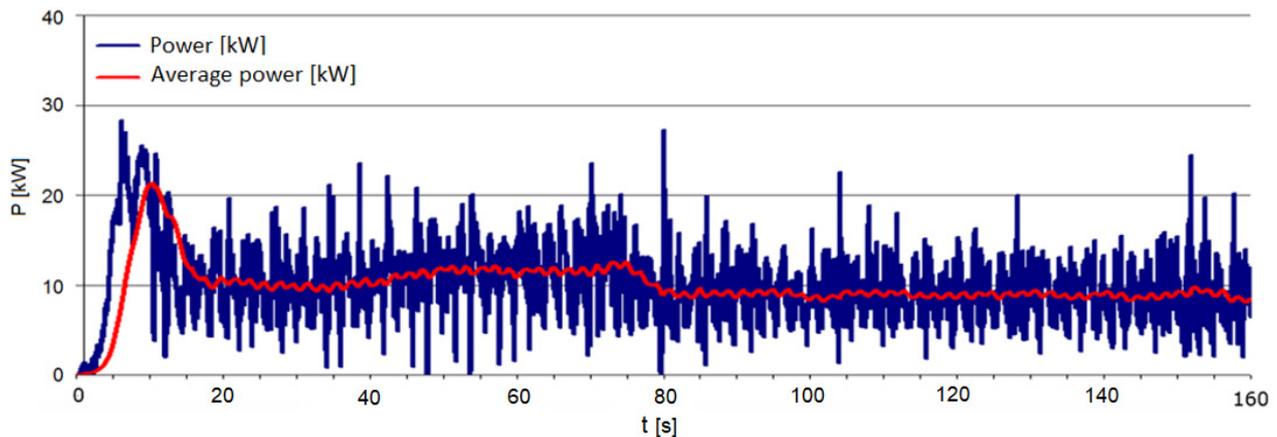


Figure 3. Time process for conveyor drive power consumption.

To decompose the time series of the output signal, a moving average was used, which is the arithmetic mean of the series values from the last N measurements. The following relationship was used to calculate the average value:

$$P_{el} = \frac{1}{N} \sum_{n=n_0}^{n_0+N} p_{el}(n) \text{ [W]} \quad (2)$$

where its terms are defined as follows:

p_{el} —electric power [W],

n_0 —the last recorded value,

N —number of samples to be averaged (averaging period).

This allowed smoothing of the time series by partially eliminating periodic and random fluctuations.

Using information about the opening degree of the jig's discharge flap to control the conveyor speed causes a delay in the system. The use of a classic control system (control in a closed system with a PID controller) may have a destabilizing effect on control quality. Therefore, a modified control system with the Smith predictor was used (Figure 4). There are two feedback loops in this system. They operate so that the controller can predict the behavior of the actual process, which is presented in the system as an object with a delay [13,14]. In turn, the model of the waste product collection process is a model with no delays, and provides the controller with information about the facility's reaction in advance by time T .

This research presents an experiment in which the traditional PI controller was replaced with a fuzzy controller. The experiment was carried out in two stages: in the first stage, a fuzzy controller with a PI structure was used (Figure 4a), and in the second stage, a PD structure was used (Figure 4b).

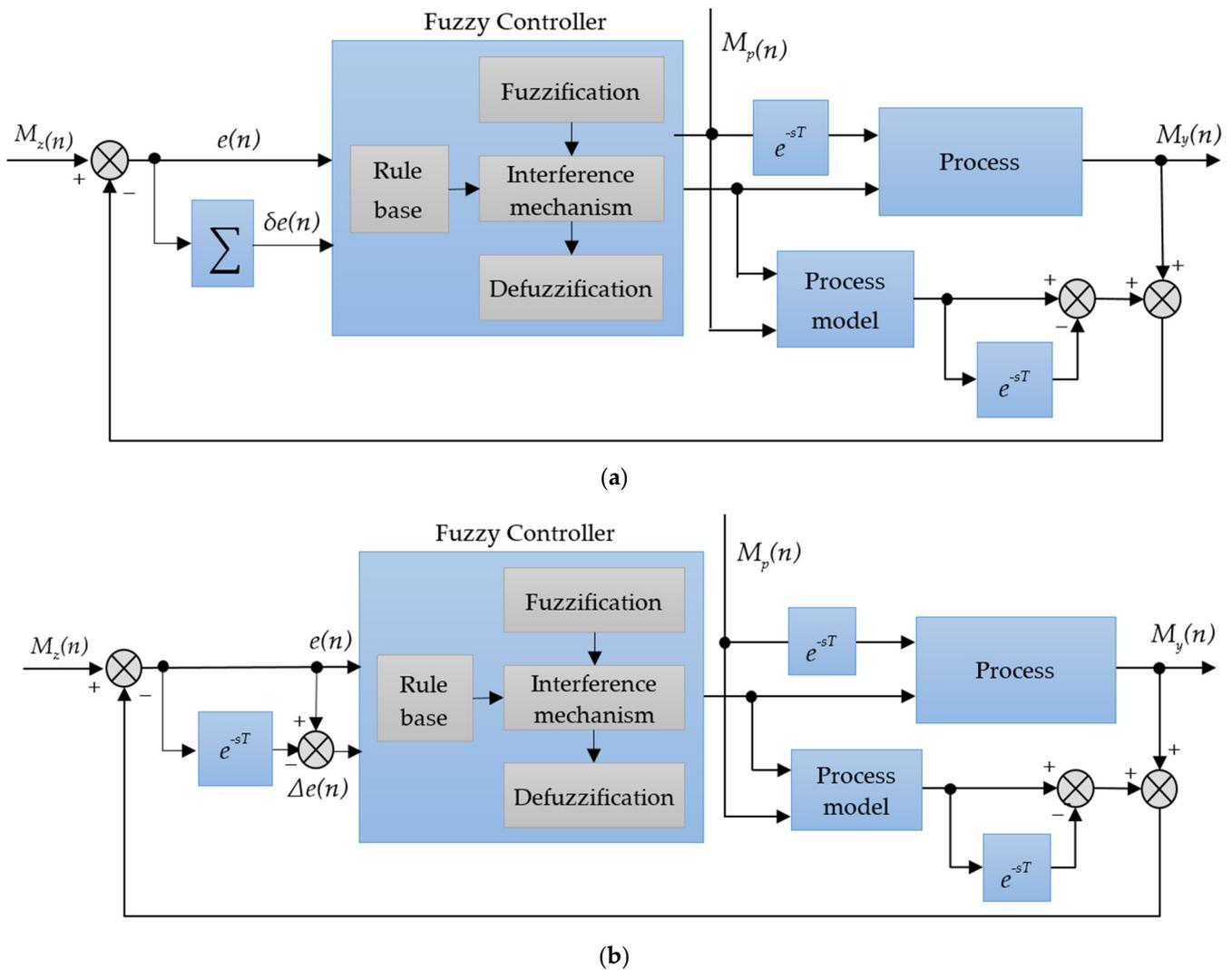


Figure 4. Control system diagram with fuzzy controller: (a) PI structure, (b) PD structure, M_z —set value of the transported product weight [kg], M_p —sum of degrees of opening the discharge flaps in the jig [%], M_y —current weight of transported heavy product [kg].

In the system, a model of the following structure was used [7]:

$$\begin{aligned}
 y_1(i) = & \frac{11.27+11.27z^{-1}}{1-0.4262z^{-1}+0.3759z^{-2}-0.9496z^{-3}}u_1(i) \\
 & + \frac{2888-3687z^{-1}}{1-0.2933z^{-1}-0.9704z^{-2}+0.2859z^{-3}}u_2(i) \\
 & + \frac{1+2.571z^{-1}+3.073z^{-2}+0.5148z^{-3}}{1+0.9318z^{-1}+0.3576z^{-2}-1.169z^{-3}-0.328z^{-4}}e(i)
 \end{aligned}
 \tag{3}$$

where its terms are defined as follows:

$u_1(i)$ —discrete sequence of opening values of the discharge flaps,

$u_2(i)$ —discrete sequence of conveyor speeds,

$y_1(i)$ —discrete sequence of values of the average material weight on the conveyor,

$e(i)$ —white noise.

These are the following linguistic variables of the process state:

$$e(n) = M_z(n) - M_y(n)
 \tag{4}$$

$$\delta e(n) = \sum_{i=(n-5)}^n e(i) \tag{5}$$

$$\Delta e(n) = e(n) - e(n - 1) \tag{6}$$

The output of the controller $y(n)$ is the increase in conveyor speed, expressed using the frequency of the drive power supply, and described by a two-dimensional control surface.

$$y = f(e, \delta e) \text{ lub } y = f(e, \Delta e) \tag{7}$$

Differentiation or integration of the control error is made at each time step before being fed into the fuzzy part of the controller.

The normalized membership functions of the controller are shown in Figure 5.

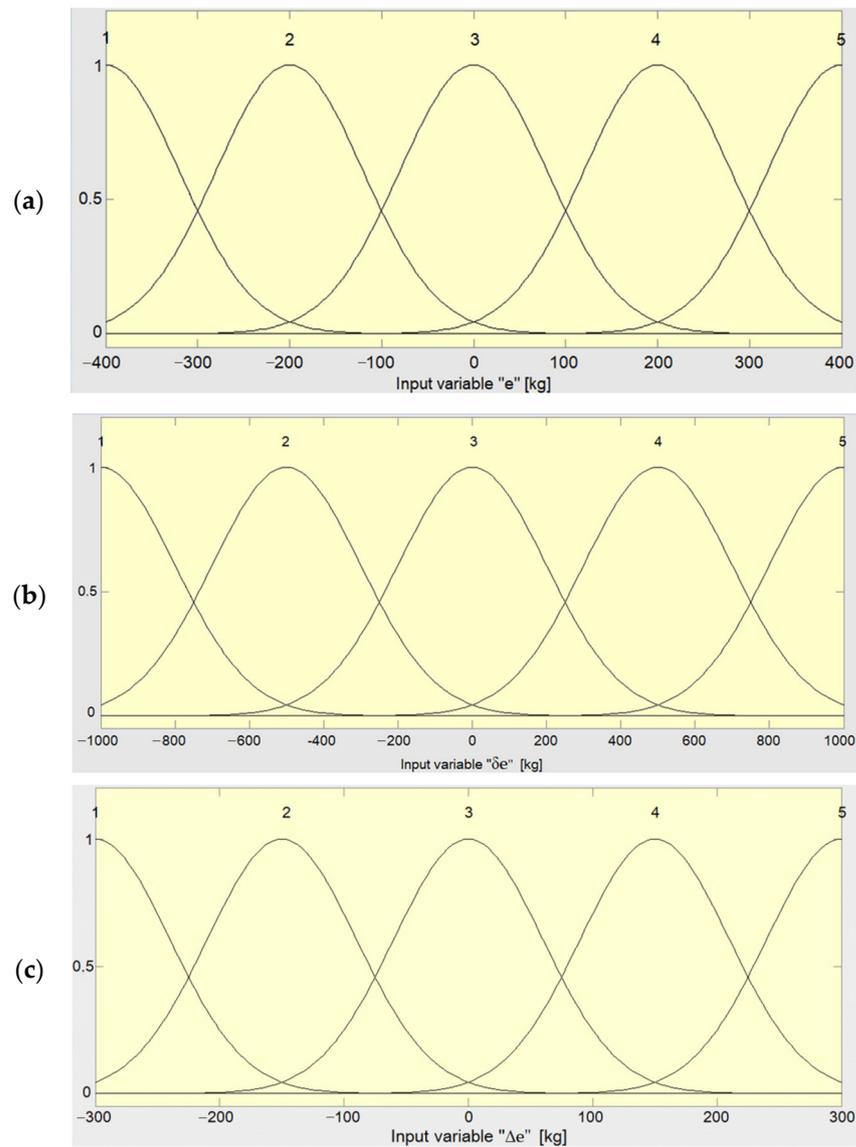


Figure 5. Cont.

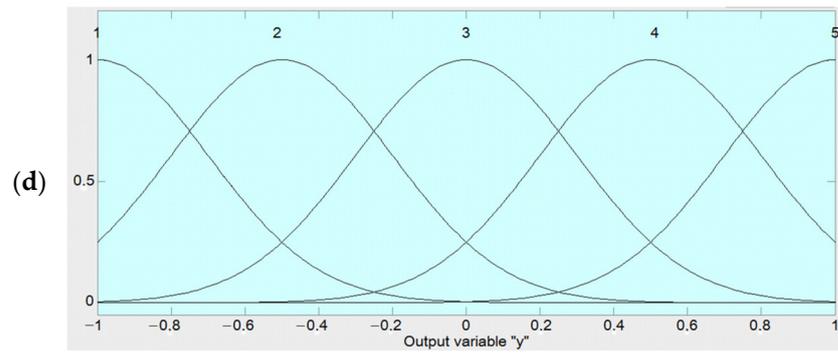


Figure 5. Membership functions for (a) $\mu(e)$, (b) $\mu(\delta e)$, (c) $\mu(\Delta e)$, (d) $\mu(y)$.

In relation to the output linguistic variable y , the used triangular membership functions are distributed unevenly in the normalized interval $[-1, 1]$.

In this study, each fuzzy rule takes the following form:

$$\text{IF } (e \text{ is } E_i) \text{ AND } ((\delta e \text{ is } E_i') \text{ or } (\Delta e \text{ is } E_i')) \text{ THEN } (y \text{ is } Y_i) \text{ END_IF} \tag{8}$$

where the values are defined as follows:

E_i, E_i' —linguistic values defined as fuzzy sets from the universe E i E' .

On the basis of the implemented functions and observations of the dynamic characteristics of the controlled process, as well as on the basis of preliminary tests analyses, fuzzy rule matrixes were established, and are presented in Table 1.

Table 1. Rule matrix.

Δy	E				
	1	2	3	4	5
1	1	1	2	3	3
2	1	1	3	3	3
3	1	2	3	4	4
4	1	3	3	5	5
5	2	2	4	5	5

A graphical interpretation of this structure is shown in Figure 6.

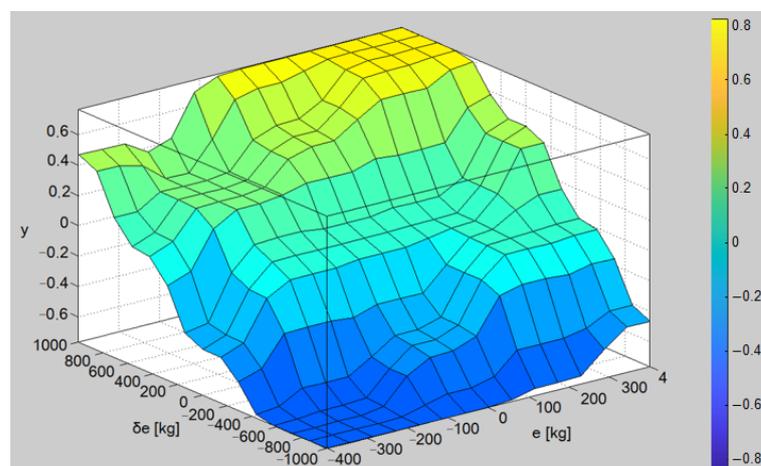


Figure 6. Control surface output of the fuzzy logic controller with a PI structure.

The developed rules contain information about the controller’s behavior for various states of input signals. These rules are the basis for the reasoning process, i.e., assessing the

degree of fulfilment of the premises of each rule. This degree, unlike the rules of classical logic, can take not only the value 0 or 1, but also fractional values in the range [0, 1]. If the degree of fulfilment of the premise of a given rule is zero, the rule will not be activated, and will not take part in the reasoning process. The higher the degree of fulfilment of a premise, the higher the contribution of a given rule in determining the resulting conclusion of the rules base.

Then, this rules base is used to determine the change in the output value based on information on error conditions and the error sum. The minimum–maximum function is used to determine the degree of output affiliation. The next step is fuzzification, which aims to transform fuzzy values into real values. For this purpose, the COA (center of area) method was used [15,16].

$$y_{COA} = \frac{\sum_{i=1}^n (\mu_z(y_i) \cdot y_i)}{\sum_{i=1}^n \mu_z(y_i)} \tag{9}$$

4. Simulation Tests of the Fuzzy Control System with Smith’s Predictor

Before the final implementation of the control system, simulation experiments were carried out using the Matlab/Simulink program. The aim of the simulation tests was to select the controller parameters based on analysis of the selected integral control quality criteria.

To assess the control quality, an indicator was adopted that is the absolute average value of the error signal. It is required in the steady state of the system that this value be as small as possible:

$$\min|\bar{e}| = \frac{1}{n-1} \sum_{i=0}^n e(i) \tag{10}$$

where the error terms are defined as follows:

\bar{e} —mean value of a control error,

$e(i)$ —discrete sequence of values constituting the control signal error.

When analyzing the controller’s operation, it is necessary to check its operation in transient states. The ITSE (integral time square error) indicator was used for this purpose. This indicator is often used in constant value systems, where the transient state is to disappear as quickly as possible:

$$\min ITSE = \min \sum_{i=0}^n e^2(i) \tag{11}$$

where the error term is defined as follows:

$e(i)$ —control signal error.

In the experiment, a control system was used, for which the block diagram, made in a simulation program, is shown in Figure 7 [17].

The block diagram shows a system with a fuzzy controller. Simulations were carried out for both the PI structure controller and the PD structure controller. During the test, in the 2000th second of the simulation, there was a change in the opening degree of the discharge flaps, from 90% to 120%. Then, the control error was recorded, and the average value as well as the ITSE were calculated. Counting the control errors was continued for another 1000 s. The obtained values are shown in Table 2.

Table 2. Assumed control quality factors.

	e	ITSE
FUZZY PI	130.66	356375893
FUZZY PD	131.79	369961286

Based on the computer simulations, it can be concluded that in relation to the selected controller settings, both control systems behaved stably. Nevertheless, better integral quality indicator results were obtained when using a system with a fuzzy controller of a PI structure. This controller was used in the industrial test.

The conveyor selected for testing removed waste material from the first two compartments of the jig (marked in green in Figure 8).

The control algorithm was implemented in the PLC controller, and the tests were performed in a steady state during normal operation of the jig node. A simplified block diagram of the control algorithm is shown in Figure 9.

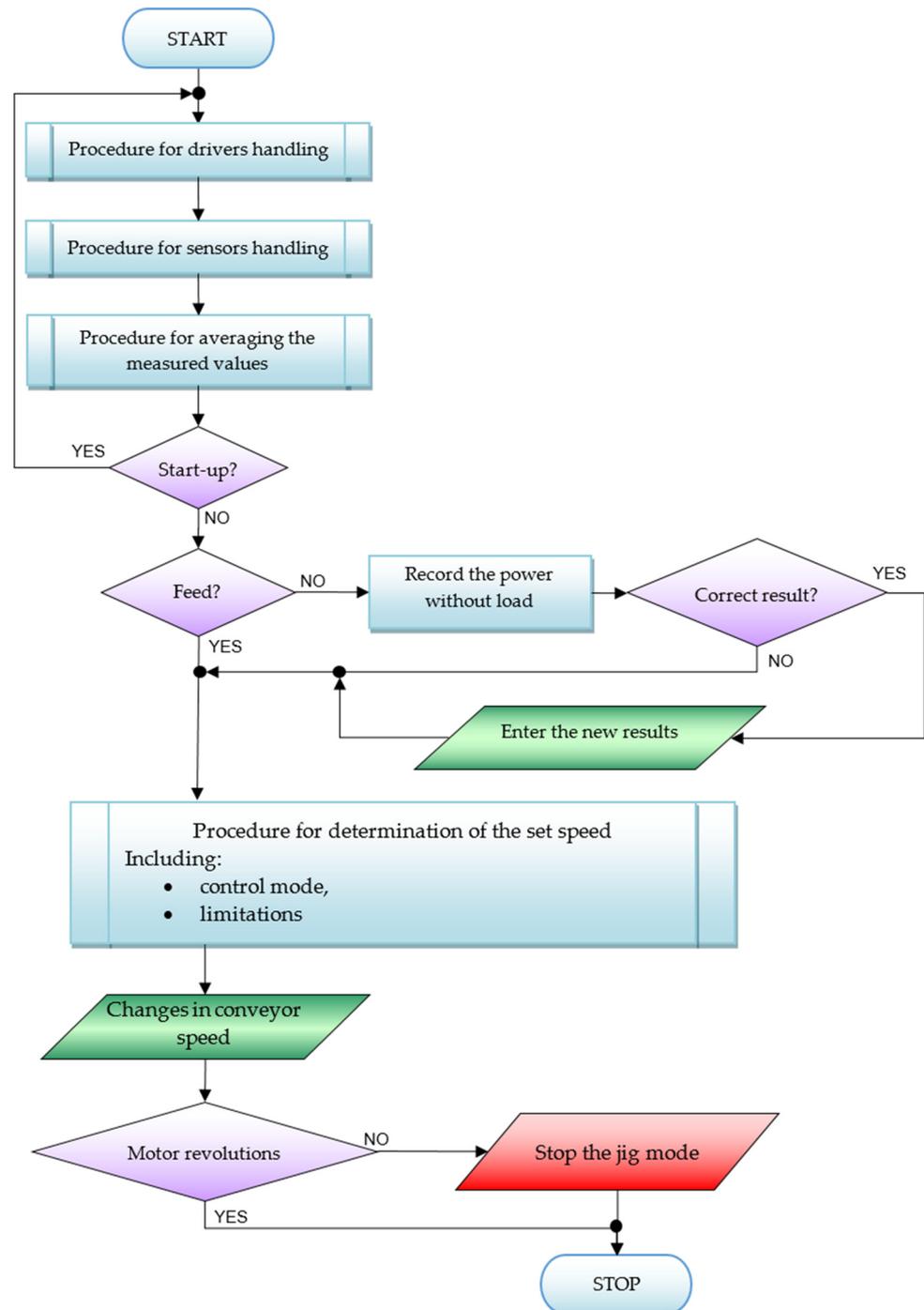


Figure 9. Block diagram of the algorithm for the bucket conveyor speed control system.

To guarantee continuity of operation and prevent the conveyor from being buried, threshold values for opening the jig discharge flaps were declared, which determine the scope of operation of the control system with a fuzzy controller. This scope of operation

took into account the sum of all opening degrees of the discharge flaps, as well as the individual opening degrees of each flap.

$$y = \begin{cases} y(i) = 50 & \text{dla } A = \{u_1(i) > 135 \cup (u_{11}(i) > 80 \cup u_{12}(i) > 80)\} \\ y(i) = 25 & \text{dla } B = \{u_{11}(i) < 5 \cap u_{12}(i) < 5\} \\ y(i) = u_2(i) & \text{dla } A \cap B \end{cases} \quad (12)$$

where its values are defined as follows:

$y(i)$ —the conveyor motor power supply frequency [Hz] (conveyor speed),

$u_1(i)$ —the sum of the degrees of opening of discharge flaps in the jig compartments I and II [%],

$u_{11}(i)$ —the degree of opening of the discharge flap in the jig compartment I [%],

$u_{12}(i)$ —the opening degree of the discharge flap of the jig compartment II [%],

A —a set of relationships meeting that result in setting the maximum conveyor speed,

B —a set of relationships meeting that result in setting the minimum conveyor speed.

According to the relationship presented above (implemented in the procedure for determining the set value of block 10 in Figure 7), if the sum of the opening degrees of the discharge flaps of both compartments (feeding the conveyor) is greater than 135%, or the opening degree of the discharge flap in one of the compartments is greater than 80%, the algorithm sets the maximum conveyor speed (condition A). In turn, if the opening of the discharge flaps in both compartments is less than 5%, the algorithm sets the minimum conveyor speed (condition B). If conditions A and B are not met, the speed is controlled by a predictive control system with a fuzzy controller.

The control system enables switching to manual control mode. In this mode, the set value of the conveyor speed is determined by the operator, which is entered in the operator panel. Information from the impulse speed sensor is monitored throughout the algorithm's operation. A lack of impulses causes the entire node to immediately stop and the jig's discharge flaps to close, preventing the conveyor from being buried.

Results were compared for the quality control of the material weight in the conveyor, and its distribution in the case when the conveyor operated with a classic control system and a fuzzy controller (Figure 10).

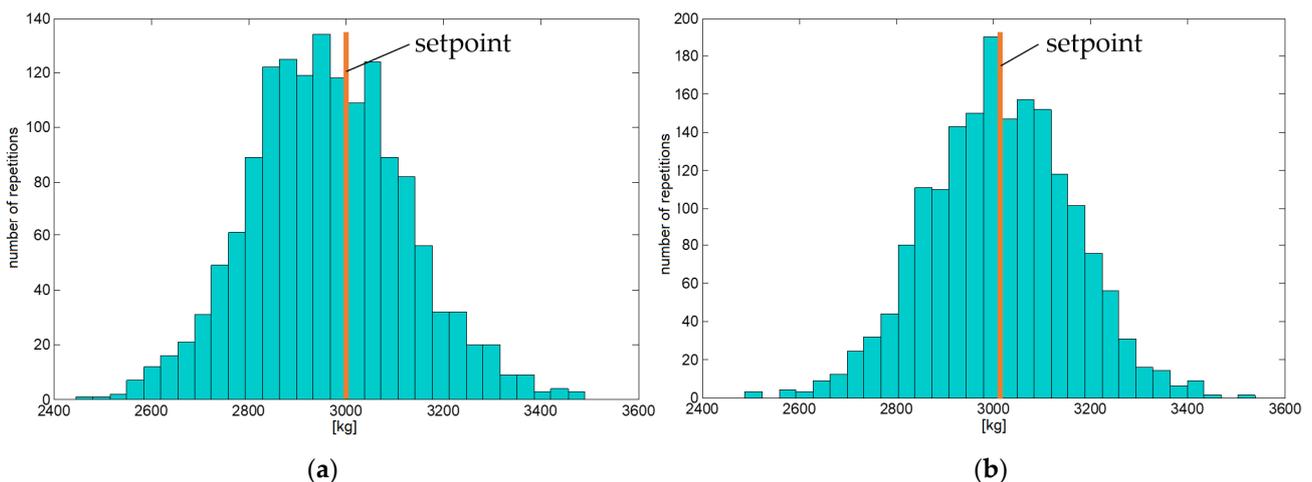


Figure 10. Changes in the distribution of material weight on the conveyor (a) PID control system, (b) fuzzy control system.

The data needed for characterization were obtained during the experiment, where the mass of the material on the conveyor with the switched-on fuzzy controller was recorded over 30 min. These data were compared with the historical waveform recorded, while the conveyor was operating with a classic controller (system with a PID controller) at the same time. In both cases, the feed was delivered to the jig with a capacity of approximately

130 kg/s. The set weight of the material on the conveyor was 3000 [kg], and was selected in such a way that with even distribution of the material, the buckets were filled to a level of 80%. The mean values and standard deviations of the waveforms are shown in Table 3.

Table 3. Weight of the material on the conveyor in the cases of two control systems.

Variant	PID [kg]	Fuzzy [kg]
Mean value	2934	3023
Standard deviation	159.8	148.3

Comparing the distributions presented in Figure 9, it can be concluded that the introduction of a speed control system with a fuzzy controller improves the results, both in terms of stabilizing the mass of the transported material, as well as in terms of the degree of conveyor bucket filling (larger mass of material on the conveyor).

6. Conclusions

This study presented test results from increasing the efficiency of a bucket conveyor operating in a jig beneficiation plant. The main goal of the research was to develop and implement a new control algorithm that enables feeding the buckets constantly, which should reduce energy consumption and extend the conveyor's service life. This research also presents the results of simulations and industrial tests using a control system with a Smith predictor and a fuzzy controller. Based on these tests, the following conclusions can be drawn:

1. The linear model in the form of an operator transfer function was suggested to describe the dynamics of the conveyor load as a response to a change in the intensity of the bottom product stream leaving the jig. The tests showed that the adopted structure of the control system with such a model reflects the dynamics of the facility well.
2. Since the modeled process is in fact non-linear, and its output (mass of the transported material on the conveyor) is affected by a number of other parameters, a significant decrease in model compliance can be expected as we move away from the operating point that was established when determining the model parameters. However, this does not limit the usefulness of the presented object control model, which was confirmed by the test results.
3. In the control system with a fuzzy controller, a smaller control error was observed than in the case of a PID controller. This proves the correct operation of the system in steady states, in which the material flow rate is stable.
4. The integral time square error determined in the system with a fuzzy controller is smaller, which proves that this controller has better dynamics compared to the PID controller, resulting in the transient waveform disappearing faster.
5. In the case of large disturbances in feeding the material into the conveyor, the control signal becomes saturated, which causes overshoots and worsens the control effects. This was seen when using both the fuzzy controller and the PID controller.
6. Further analysis is justified for the effects of using the algorithms with various methods of compensating unfavorable phenomena accompanying the control of non-linear processes.
7. Further tests will include a more detailed analysis of the system with a fuzzy controller, taking into account such disturbances as changes in the feed flow rate. Successful tests will allow implementation of a fuzzy controller to control bucket conveyor operation. Using other structures for testing the control systems is planned, e.g., the Reswick controller or MFC robust control systems. Another possibility is to use a non-linear model. However, this may require the use of a PLC controller with greater computing power, or the use of an independent controller in relation to the controller that manages jig node operations. This approach may turn out to be economically unprofitable.

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Appendix A

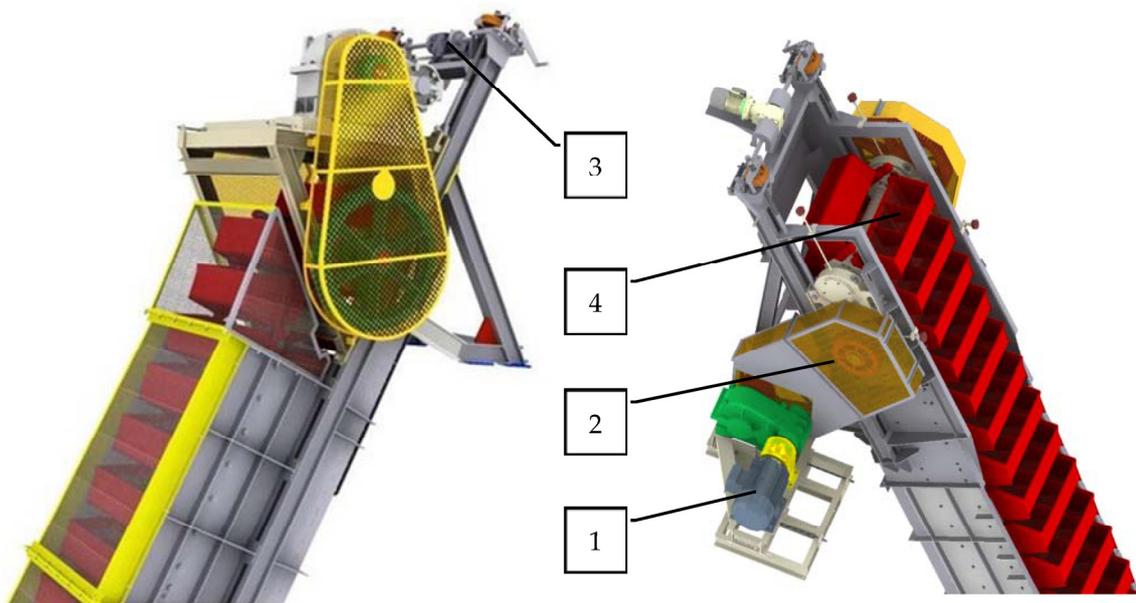


Figure A1. KOMAG bucket conveyor B-1000. 1—drive, 2—gear, 3—tensioning station, 4—buckets.

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