TOMO BENOVIĆ*, IGOR MILJANOVIĆ**, SLOBODAN VUJIĆ**

FUZZY MODEL OF AUTOGENOUS SUSPENSION COAL CLEANING

MODEL ROZMYTY PROCESU WZBOGACANIA WĘGLA W ZAWIESINIE AUTOGENICZNEJ

The paper presents one of the possible approaches to fuzzy logic modeling of coal cleaning in autogenous suspension. In the scope of reviewing the problem in general, the process algorithm and the structural model of coal cleaning were set up. The paper deals with the flow of fuzzy logic model creation following the example of coal cleaning plant of the "Bogutovo selo" open pit mine of the Mine and Thermal Power Plant Ugljevik. The model is set up on the MATLAB software platform. Fuzzy model testing results, presented at the end of paper confirms applicability and reliability of the model. The discrepancies between the model and the real process parameters are within the limits of allowed industrial error.

Keywords: fuzzy logic, modeling, coal cleaning, autogenous suspension, Parnaby, Ugljevik

W pracy przedstawiono jedną z dostępnych metod modelowania rozmytego zastosowaną do modelowania procesu wzbogacania węgla w zawiesinie autogenicznej. Analiza problemu obejmuje przedstawienie algorytmu procesu wzbogacania oraz jego model strukturalny. W pracy przedstawiono proces tworzenia modelu rozmytego na przykładzie zakładu wzbogacania 'Bogutovo selo' przy kopalni odkrywkowej będącej częścią zakładów górniczych i elektrowni Ugljevik. Model stworzono przy wykorzystaniu platformy MATLAB. Wyniki testowania modelu rozmytego zaprezentowane w artykule potwierdzają przydatność i wiarygodność modelu. Rozbieżności pomiędzy wynikami modelowania a parametrami rzeczywistych procesów mieszczą się w dopuszczalnych przy procesach przemysłowych granicach tolerancji błędu.

Słowa kluczowe: logika rozmyta, modelowanie, wzbogacanie węgla, zawiesina autogeniczna, Parnaby, Ugljevik

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* COAL AND THERMAL POWER PLANT UGLJEVIK, BOSNIA AND HERZEGOVINA
** UNIVERSITY OF BELGRADE, FACULTY OF MINING AND GEOLOGY, 7, DJUSINA ST., 11000 BELGRADE, SERBIA
TEL: +381 11 32 38 564; FAX: +381 11 33 47 934, E-mail: vujic@rgf.bg.ac.rs

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1. Introduction

Coal cleaning in autogenous suspension is a process the effectiveness and efficiency of which is influenced by a number of factors. In a system sense it is a relatively simple process with several sequential phases. In a technological sense, the process is made complex by fluid and often difficult to predict variations in run-of-mine coal properties together with the deviation from the desired regime of process parameters (Cierpisz). The profession is well aware of this problem, and it is accepted as the generator for seeking the efficient answer through decision support and management of coal cleaning process.

Aside from achieving the demanded quality of the clean coal, expressed through ash, humidity and sulfur content, as well as the heat value, coal cleaning process goals are the: minimization of costs and production reliability, energetic efficiency, maximum utilization of time and capacity within the cleaning plant, ecological safety, etc. It is typical for coal cleaning plants in general to operate with several technological cycles, and that variations of input and process parameters have immediate influence on the plant operation effects. In this ambience, successful management of the technological process both in extended and in real time, is difficult to achieve without the adequate mathematical-modeling support in decision making (Gupta). Functions of mathematical models in the extended time are related to their application in design, testing, experimental analysis, research, examining, etc. In real time, mathematical models have the process (logistic) function as the expert or consulting in assisting the system in decision making during the coal cleaning process.

The starting assumption of the successful mathematical modeling of coal cleaning process is the acquisition and processing in real or extended time of a number of variable data, different influences to the process, mutual correlative connections that are difficult to measure, difficult identification of priorities and influence ranks (Kijo-Kleczkowska). The aggravating circumstance is that processes such as these have non-linear properties in general, as a consequence of limitation, saturation, remanence and hysteresis of process flows (King).

Research on this subject was primarily directed toward the deterministic mathematical-modeling approaches for support to decision making, relying on an assumption on the temporal invariability of descriptive coefficients and variables linearity. Regardless of the fact that coal cleaning processes are slow (variations are not happening in seconds or milliseconds), the assumption on temporal invariability of descriptive coefficients is not in agreement with real developments. The general conclusion on the outcome of deterministic mathematical-modeling approaches application is that they did not produced expected results (Miljanović, 2008a).

During the few last decades, the intensive development of soft computing, fuzzy theory and data mining brought upon their application in different areas of science and industry as well as in mining, and opened new opportunities for mathematical modeling of dynamic systems and processes (Kahraman). There are two logical reasons for setting the fuzzy mathematical model in the foundation of the system for decision support and management of coal cleaning process. One of the reasons is the fuzzy nature of the coal cleaning process and its proximity – "closeness" with the *fuzzy logic* idea. The other reason is the already mentioned insufficient efficiency of deterministic approach for modeling process with variations of parametric attributes that are difficult to predict (Kaula).

Opposed to the fact that potentials of fuzzy logic application are vast, the insufficient education of professionals and their common opposition to the new, are influencing this area of development and research in mining and mineral processing to be still in its opening phase.

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2. Process algorithm and the structural model of coal cleaning

The topological similarity of coal cleaning in autogenous suspension allows for the general object-oriented algorithm and the structural model of the process to be set up, as the starting point in reviewing the technological and monitoring-management flows, and necessary in setting up the process mathematical model.

By connecting the sequential technological operations from the delivery of run-of-mine coal all the way to the final product – clean coal, the general object-oriented process algorithm is defining the functional structure of the autogenous suspension coal cleaning technology, Figure 1.
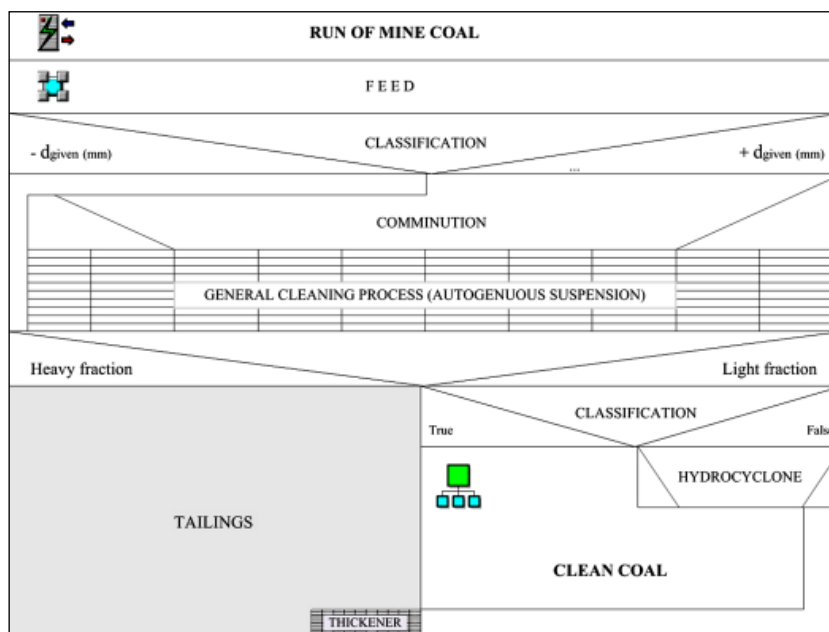

Fig. 1. Process algorithm of coal cleaning in autogenous suspension

According to the object-oriented process algorithm and having in mind the technical-technological and safety demands for the autogenous suspension coal cleaning, for the purpose of managing the technological process following the regime set, it is necessary to establish the physical and logical topology of the monitoring-management system on the foundation of centralization and selective passability from the production-executive to the operative-monitoring and higher hierarchical-management levels (Miljanović, 2008b). These are the conditions upon which the general structural model of coal cleaning process, presented on Figure 2, is set up.

In the structural model two mutually joined processes are present, the production and monitoring-management process. The production flow consists of run-of-mine coal delivery, comminution, autogenous suspension separation in a drum and cyclone. Process products are the clean coal and the waste.
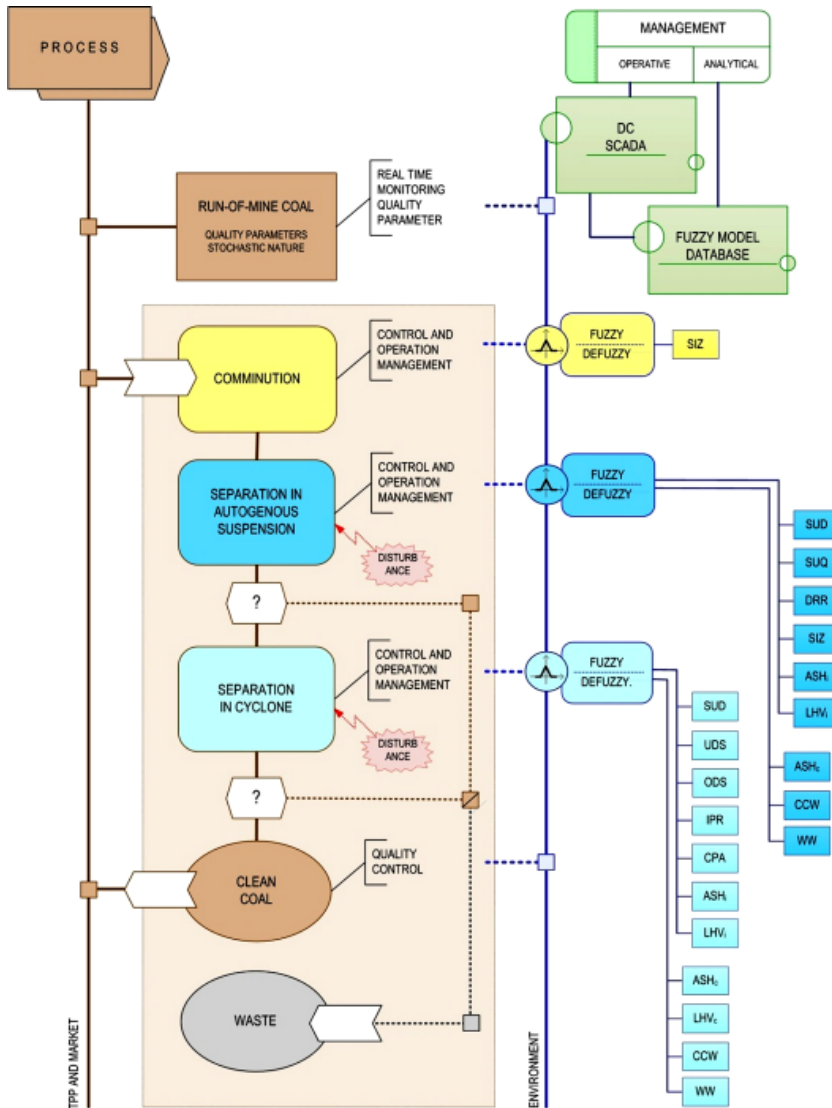
Fig. 2. Structural model for support to decision making and real time management of coal cleaning process

The information-management flows connects the monitoring-management level with measurement/executive points in the production process, established for the purpose of real time measurements of run-of-mine coal quality, control and management of comminution and autogenous suspension and cyclone separation. The Information-management products are the data from the production process and the feedback corrective actions to the process. The top of hierarchical structure of the monitoring-management part of the structural model are the Dispatcher and the management. According to the structure model, the Dispatcher is monitoring the proc-

ess in real time, making decisions and managing the process, while extended time management is monitoring and analyzing production effects, making conclusions and issuing decisions on potential corrections of the production process.

Due to complex measuring ability and hard-to-predict variability of process parameters, coal cleaning systems are highly demanding from the information-management aspect (Miljanović, 2008b; Sen). This engineering demanding task is today regularly solved by utilizing computer integrated technologies. For illustrative purpose, the topological schematic of the remote monitoring and management system of the "Bogutovo selo" brown-lignite coal open pit mine at the Ugljevik Mine and Thermal power plant (Vujić, 2007), having in its structure the subsystem for monitoring and management of the coal cleaning plant is presented in Fig. 3. The fuzzy model of coal cleaning, presented in this paper, was developed following the example of Parnaby plant at this mine. Therefore, the selection of this topology as the illustration of the integrated monitoring-management system is not coincidental.

Under the assumption that the integrative, technical, technological, organizational and logistics conditions are met, to achieve the efficiency of monitoring-management system of the coal cleaning plant means, among other things, the fuzzyfication and defuzzyfication of process parameters on three technological positions (Takagi, Bangian). According to the structural model, presented in Figure 2, the fuzzyfication and defuzzyfication of process parameters should be established on the following positions:

    a. Coal comminution;
    b. Coal cleaning in autogenous suspension; and
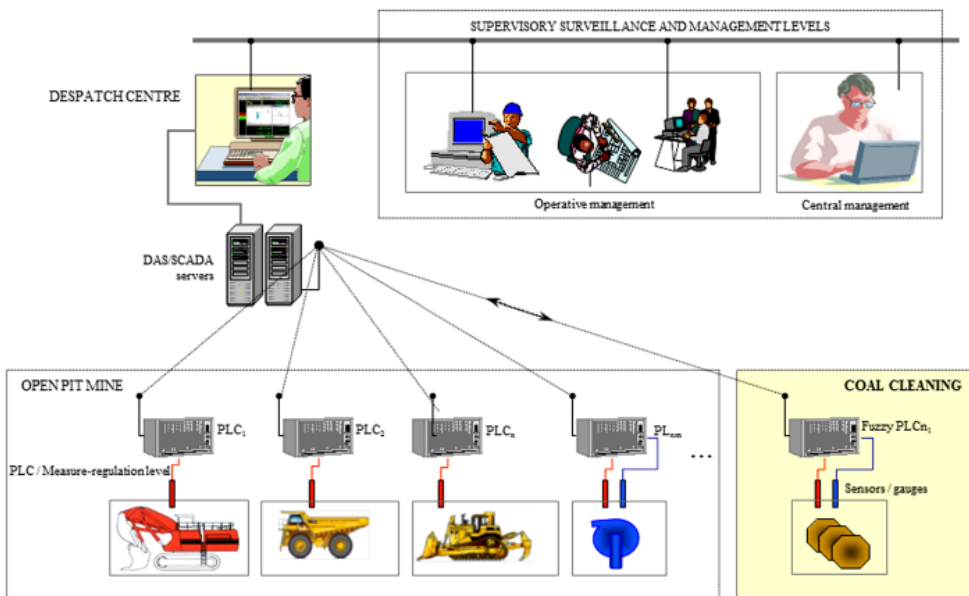   c. Cyclone separation.

Fig. 3. Topology of the monitoring-management system of the "Bogutovo selo" open pit mine with the integrated subsystem for coal cleaning in autogenous suspension (Vujić, 2007)

One of the assumptions of the functional efficiency of system for decision making support and management of coal cleaning process is an integrated hierarchical structure, which must have at least three levels: measurement/executive, communication and monitoring-management. This structure ensures that (Vujić, 2007):

1. Variable data are efficiently processed;
2. Response is provided in real time with adequate decisions;
3. The system is variable, operative and scalable;
4. Controllers' logic is efficiently realized;
5. Data is transferred from the process toward the Dispatch center and selectively toward the higher decision – making levels;
6. Data are efficiently processed, interpreted and presented in real time;
7. Data are filtered and selectively distributed;
8. Feedback on the key processes within the production system are enabled;
9. Additional information (in extended time) is available.

One of the assumptions for efficient processing of technological parameters, fast real time response, variability, operability and scalability of decision making, and the efficient realization of managing decisions is the existence of an adequate mathematical model of the process, that can have either simulation or expert-consulting function in a monitoring-management whole (Cierpisz, King). What function will model have, depends on its functional-logical construction and the manner of implementation into the decision – making support system.

3.   Foundation of fuzzy model creation

Fuzzy model of coal cleaning in autogenous suspension, presented in this paper, was developed following the example of Parnaby plant at the "Bogutovo selo" open pit mine of the Mine and Thermal Power Plant in the Republic of Srpska. The coal is mainly used by the Thermal Power Plant "Ugljevik 1", with smaller quantities distributed via the market. The annual production amounts to 2 millions of tons of coal and 1,500 (GWh) of electric power. The deposit is layered and the coal is variable in quality. From the roof layers, the coal is not used directly, before the utilization it is cleaned in a technological procedure with three sequential phases:

a. Run-of-mine coal comminution (–100 + 0 mm);
b. Classification and cleaning of coal;
c. Waste water cleaning.

Cleaning of coal sized above 5 (mm) is accomplished in a Parnaby drum, while fines are separated in cyclones. Figure 4 presents the general flowsheet of the technological process of autogenous suspension coal cleaning at the processing plant of the "Bogutovo selo" open pit mine (Vujić, 2007). The flowsheet was set up upon the technological schematic of the coal cleaning plant, principles of the object-oriented process algorithm and the structural model for decision – making support and management of coal cleaning process in real time.

Since several parameters influence the efficiency of the technological process, for the purpose of estimating as few model parameters as possible Vujić (2011b) and in order to describe the cleaning process as well as possible, the most important are:

- Technological parameters – density, suspension quantity and drum rotation ratio;
- Coal quality parameters – contents of ash, sulfur, humidity, the Lower Heat Value and the mass ratio of clean coal and waste.
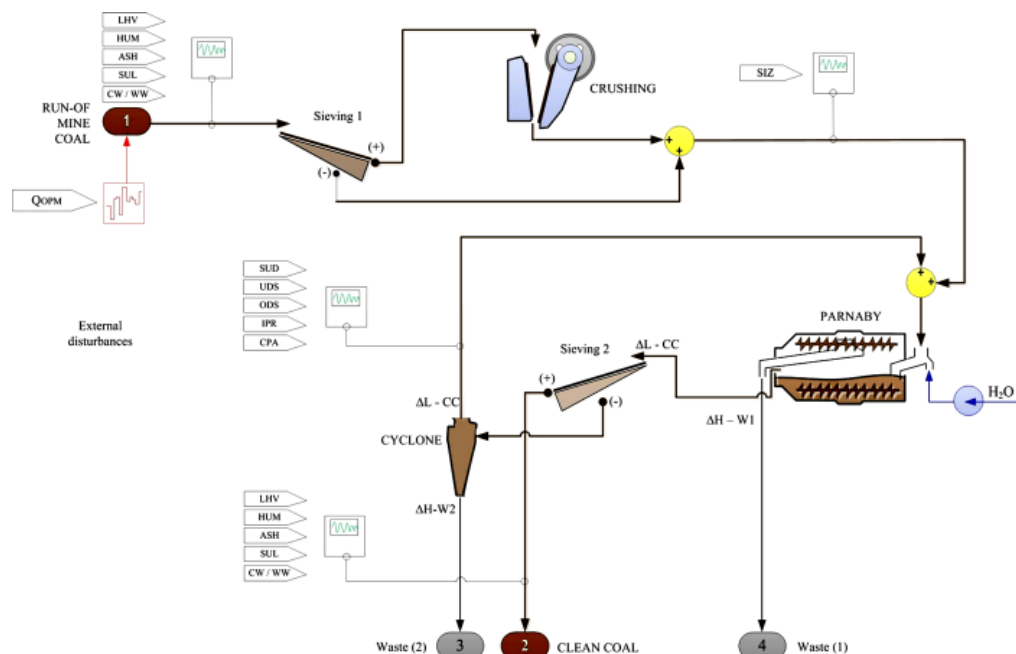
Fig. 4. General technological flowsheet of coal cleaning used in the plant of the "Bogutovo selo" open pit mine

By means of mathematical-statistical processing of data on coal cleaning plant at the "Bogutovo selo" open pit mine between 2006 and 2009, process parameters were generated and used in developing the fuzzy model, Table 1. Beside the review of process parameters, Table 1 shows variability ranges, average values with probabilities and middle of the range values.

TABLE 1

Process parameters of coarse coal fractions cleaning

Parameter	Mark	Measure-ment unit	Variability range		Average value	Probabi-lity (%)	Middle of the range
			Min	Max			
1	2	3	4	5	6	7	8
TECHNOLOGICAL PARAMETERS							
Suspension density	SUD	g/cm^3	1.3	1.8	1.55	67	1.7
Suspension quantity	SUQ	%	70	80	75	67	75
Drum rotation ratio	DRR	min^{-1}	12	30	21	69	14
INPUT PARAMETERS (RUN-OF-MINE COAL)							
Size of run-of-mine coal (+5 mm)	SIZ	%	50	95	72.5	67	80
Run-of-mine coal ash content	ASHi	%	13.92	43.55	25.03	72	28.73
Run-of-mine coal Lower Heat Value	LHVi	kJ/kg	6.163	15.145	10.664	71	10.654
Run-of-mine coal sulfur content	SULi	%	1.35	7.73	4.28	69	4.54
Run-of-mine coal humidity content	HUMi	%	13.15	38.05	27.15	66	25.98

1	2	3	4	5	6	7	8
OUTPUT PARAMETERS (CLEAN COAL)							
Clean coal ash content	ASHc	%	10.59	30.48	17.52	66	20.53
Clean coal Lower Heat Value	LHVc	kJ/kg	7.425	16.500	12.158	68	11.963
Clean coal sulfur content	SULc	%	1.30	7.3	4.00	68	4.30
Clean coal humidity content	HUMc	%	21.00	41.15	30.50	68	31.07
Clean coal weight ratio	CW	%	75	89	86.12	70	82
Waste weight ratio	WW	%	11	25	13.88	69	18

The fuzzyfication of process parameters precede the creation of fuzzy model of coal cleaning process, meaning that fuzzy ranges are defined, together with the verbal values of the parameters (Vujić, 2011a), Table 2. In converting the numeric into the linguistic values of process parameters, categorization with three levels was applied: L – low/small, M – medium, H – high/large.

In the matrix of mutual dependencies, Table 3, the sulfur was left out because of insignificant differences between its content in the run-of-mine and the clean coal (the discrepancy ≤ 3.7%). Since it is a wet separation procedure, there is no logic in correlating the humidity content of the input and output coal, therefore the humidity parameter was left out in the matrix of mutual dependencies.

TABLE 2

Fuzzyfication of coarse coal fraction cleaning process parameters

Parameter	Mark	Measurement unit	Fuzzy range	Linguistic value
1	2	3	4	5
TECHNOLOGICAL VARIABLES				
Suspension density	SUD	(g/cm^3)	<1.5	S
			1.5-1.7	M
			> 1.7	H
Suspension quantity (related to the nominal quantity)	SUQ	%	< 70	S
			70-80	M
			> 80	H
Drum rotation ratio	DRR	min^{-1}	< 12	S
			12-18	M
			> 18	H
INPUT VARIABLES				
Run-of-mine coal size (+5 mm)	SIZ	%	< 75	S
			75-85	M
			> 85	H
Run-of-mine coal ash content	ASHi	%	< 20.00	S
			20-25	M
			> 25.00	H
Run-of-mine coal Lower Heat Value	LHVi	kJ/kg	< 9.000	S
			9.000-11.500	M
			> 11.500	H

1	2	3	4	5
Run-of-mine coal sulfur content	SULi	%	< 3	S
			3-5	M
			> 5	H
Run-of-mine coal humidity content	HUMi	%	< 23	S
			23-29	M
			>29	H
OUTPUT VARIABLES				
Clean coal ash content	ASHc	%	< 15.00	S
			15.00-20.00	M
			> 20.00	H
Clean coal Lower Heat Value	LHVc	kJ/kg	< 10.500	S
			10.500-12.500	M
			> 12.500	H
Clean coal sulfur content	SULc	%	< 2.7	S
			2.7-4.7	M
			> 4.7	H
Clean coal humidity content	HUMc	%	< 26	S
			26-32	M
			> 32	H
Clean coal weight ratio	CW	%	< 80.00	S
			80.00-90.00	M
			> 90.00	H
Waste weight ratio	WW	%	< 10.00	S
			10.00-20.00	M
			> 20.00	H

Interpretation: L – low / small, M – medium, H – high / large.

TABLE 3

Mutual dependency matrix of coarse coal fractions cleaning process parameters

Parameter	Mark	Action			
		ASHc	LHVc	CW	WW
Suspension density	SUD	R	D	D	R
Suspension quantity	SUQ	R	D	D	R
Drum rotation ratio	DRR	R	D	D	R
Coal size	SIZ	D	R	R	R
Run-of-mine coal ash content	ASHi	R	D	D	R
Run-of-mine coal Lower Heat Value	LHVi	D	R	D	R

Outcomes: R – rises, D – drops.

4. Coal cleaning fuzzy model

For the purpose of developing the fuzzy model of coal cleaning in autogenous suspension, MATLAB (MATrix LABoratory) program platform was used, with a numerical environment, enabling the vector (matrix) operations, algorithm implementation, function plotting, creation of user custom interface, etc. (Klee).

The optional program modules MuPAD and SIMULINK, with symbolic calculations and higher simulation domains are providing flexible creative possibilities in research and industrial
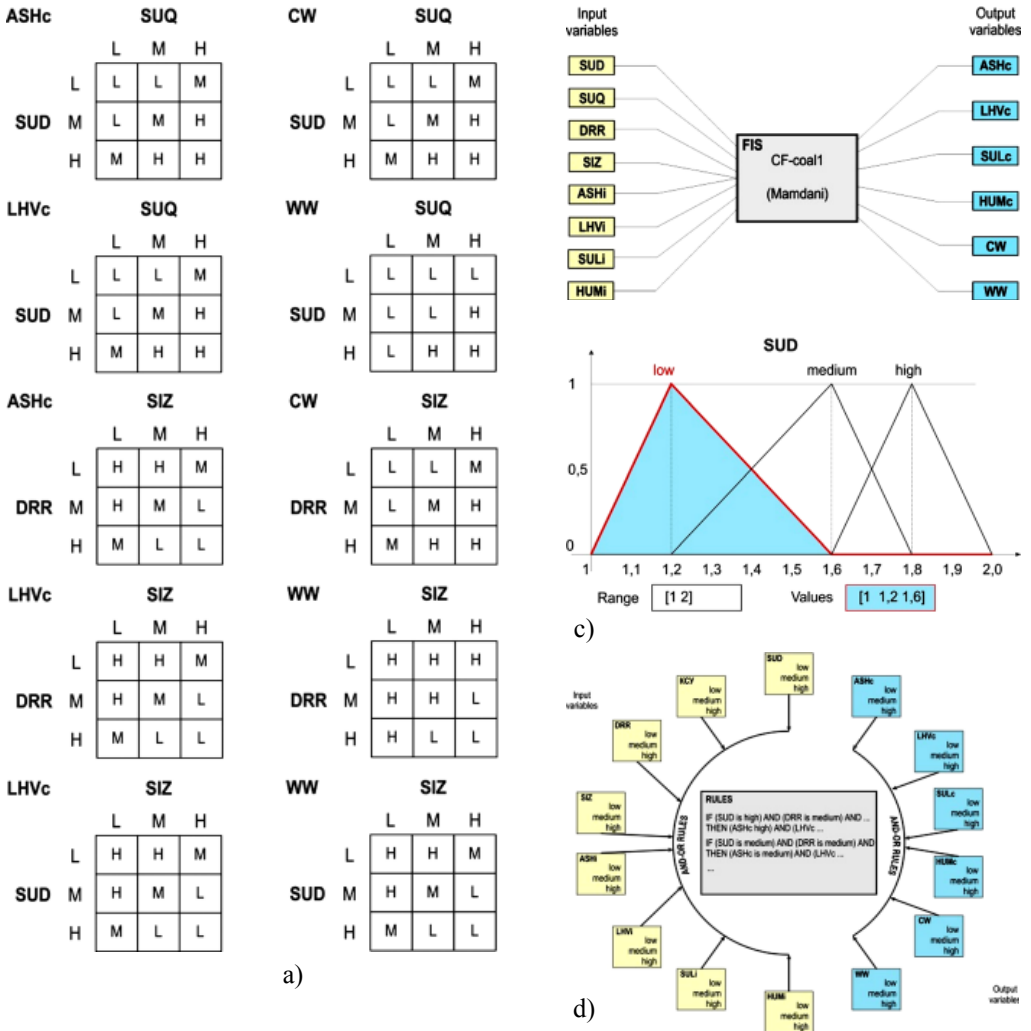
Fig. 5. Model fuzzy rules of coarser coal fractions cleaning: a) Combinatory matrices of fuzzy relations between the process parameters; b) Membership functions of process parameters in the fuzzy model; c) Assigning fuzzy values to parameters; d) Fuzzy rules creation within the model

domains, which was completely displayed in developing the coal cleaning fuzzy model. The model fuzzy rules for the process of cleaning of coarser fractions of coal were established on the foundations of the mutual dependencies matrix and the fuzzyfied parameters (Table 2).

As an immediate starting point of fuzzy process model creation, a part of model fuzzy rules created in such manner is presented as an illustration, in Figure 5. Figure 5a shows a part of combinatory matrices of process parameter fuzzy ratios for coarse coal fractions, Figure 5b the membership functions or process parameters, Figure 5c illustrates process of assigning the fuzzy values to process parameters and Figure 5d the setting of fuzzy rules in the model in a general, schematic manner. Indirectly, these figures are illustrating the sequences of coal coarse fraction fuzzy model development.

For the rationality purposes, only four of 3D graphical representations of process parameters relations created in MATLAB are presented in Figure 6.

Separation of fractions sized below 5 (mm) in cyclones was processed in a same manner as it was for the coarse coal fractions. The technological parameters are different, for this process they are: suspension density, underflow opening diameter size, overflow opening diameter size, cyclone
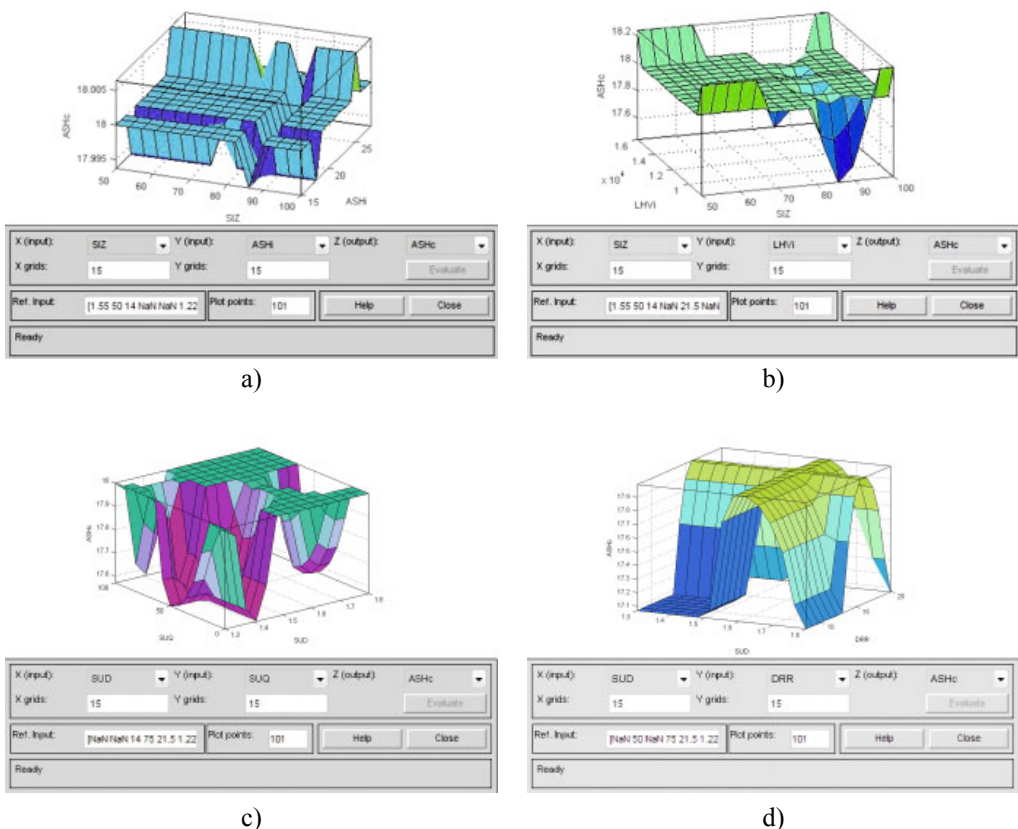

Fig. 6. Computer sequences of the fuzzy process parameters ratio:
a) SIZ/ASHi – ASHc; b) SIZ/LHVi – ASHc; c) SUD/SUQ – ASHc; d) SUD/DRR – ASHc

diameter, input pressure and the angle of cone part. The fuzzyfication of process parameters, the formation of combinatory matrices, definition of membership functions, assigning fuzzy values to process parameters and the formation of model rules are identical to the procedures described in forming the coarse coal fraction fuzzy model. Description of these details was left out of the paper, since this presentation would unnecessary increase the paper size.

For the purpose of creating the fuzzy simulation model of autogenous suspension coal cleaning for the example of the "Bogutovo selo" open pit mine processing plant, the SIMULINK program module intended for simulation of dynamic systems in a graphical environment was used. The mathematical model is occurring in a graphical, or a block-diagram form. The blocks are connected with arrows marking the simulated process flow, while the process parameters are presented with signals on the inputs and outputs of the blocks. To simplify, the model is a specification of graphical building components that can be altered, corrected and adjusted during the model development and exploitation. The block diagram of the autogenous suspension coal cleaning fuzzy simulation model, developed on the example of the "Bogutovo selo" open pit mine processing plant, is presented in Figure 7.
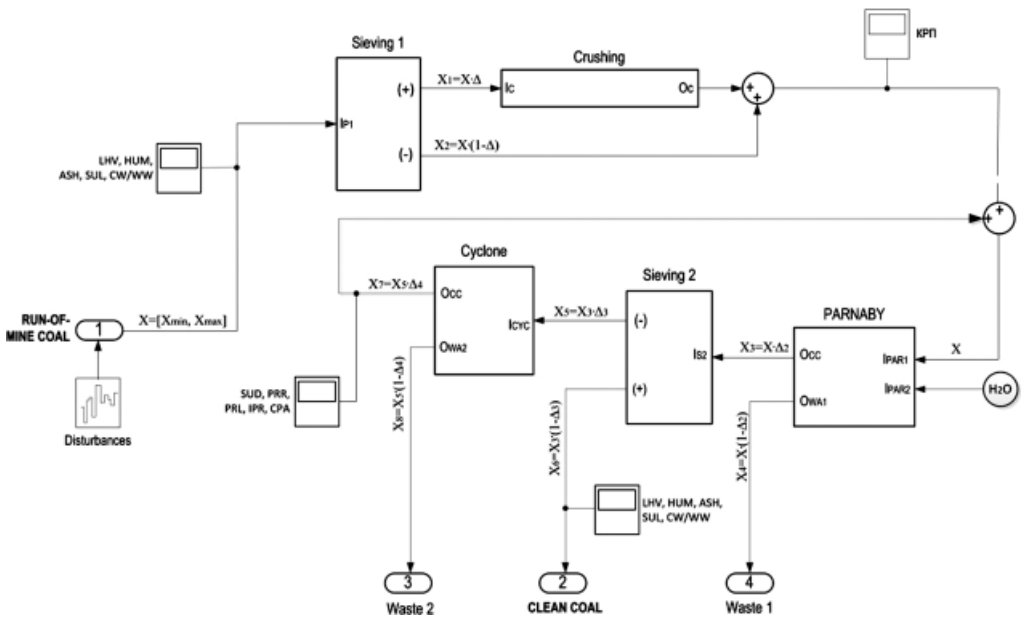

Fig. 7. Block diagram of the fuzzy simulation model of coal
cleaning at the processing plant of the "Bogutovo selo" open pit mine

5. Model testing results

Testing the validity of the developed fuzzy model was performed by a comparative analysis of simulation results and the real effects of the "Bogutovo selo" open pit mine coal cleaning plant. Apart from the conditions depicting the operation of coal cleaning plant presented in sections 3

and 4, the following were the preset values for the model: simulation time, cyclic interval, location and range of disturbances. For the simulation time, a period of 24 hours of plant operation was taken, and the cycle interval was 1 hour. The run-of-mine coal input bin, figures 4 and 7, was taken as a place for generating the disturbances in the technological process, due to variability in coal quality. The RND() function was used for generating the disturbing influences.

Model testing was performed with the iterative procedure to the "saturation" of average values of simulated process parameters. The "saturation" criteria was defined by the discrepancy limit up to ±5(%). Figure 8 shows a part of the simulation tests results, showing high, almost functional correlation of input and output model parameters. The medium correlation coefficient was 0.92, the lowest correlation coefficient is 0.87, for humidity, and the highest is 0.97, for the sulfur, Figure 9. The comparative analysis of model and real parameters, Figure 10, shows that
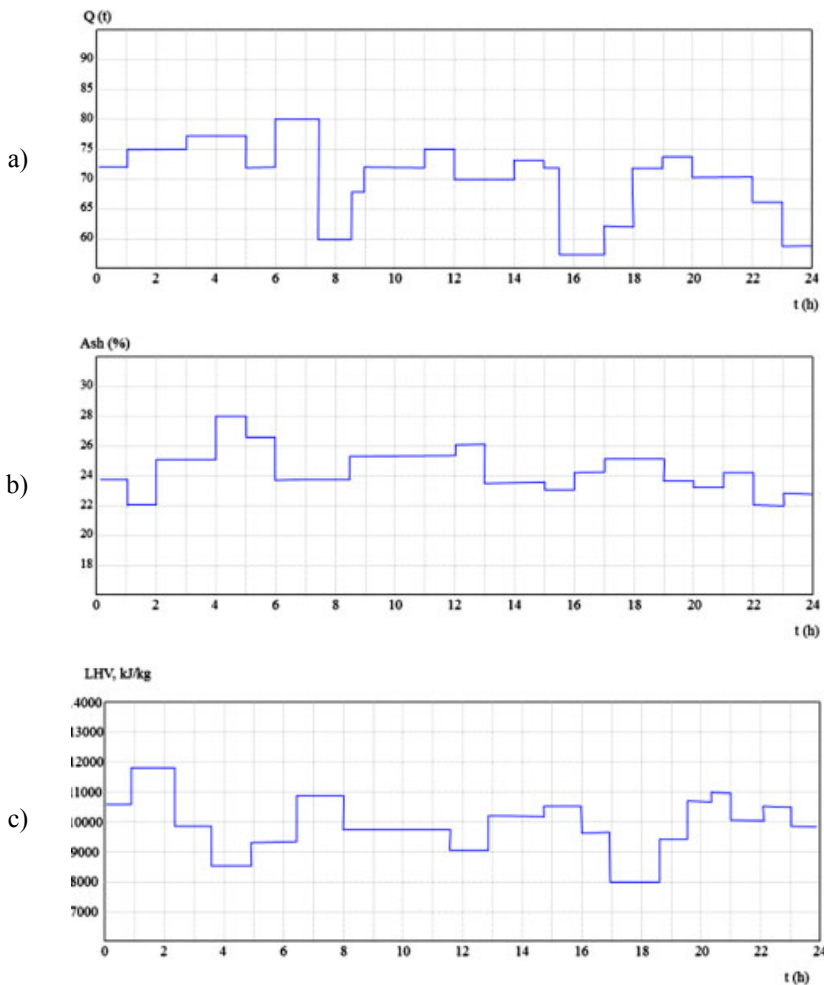
Fig. 8. Part of the simulation tests results:
a) Run-of-mine coal delivery; b) Run-of-mine coal ash content; c) Run-of-mine coal Lower heat value
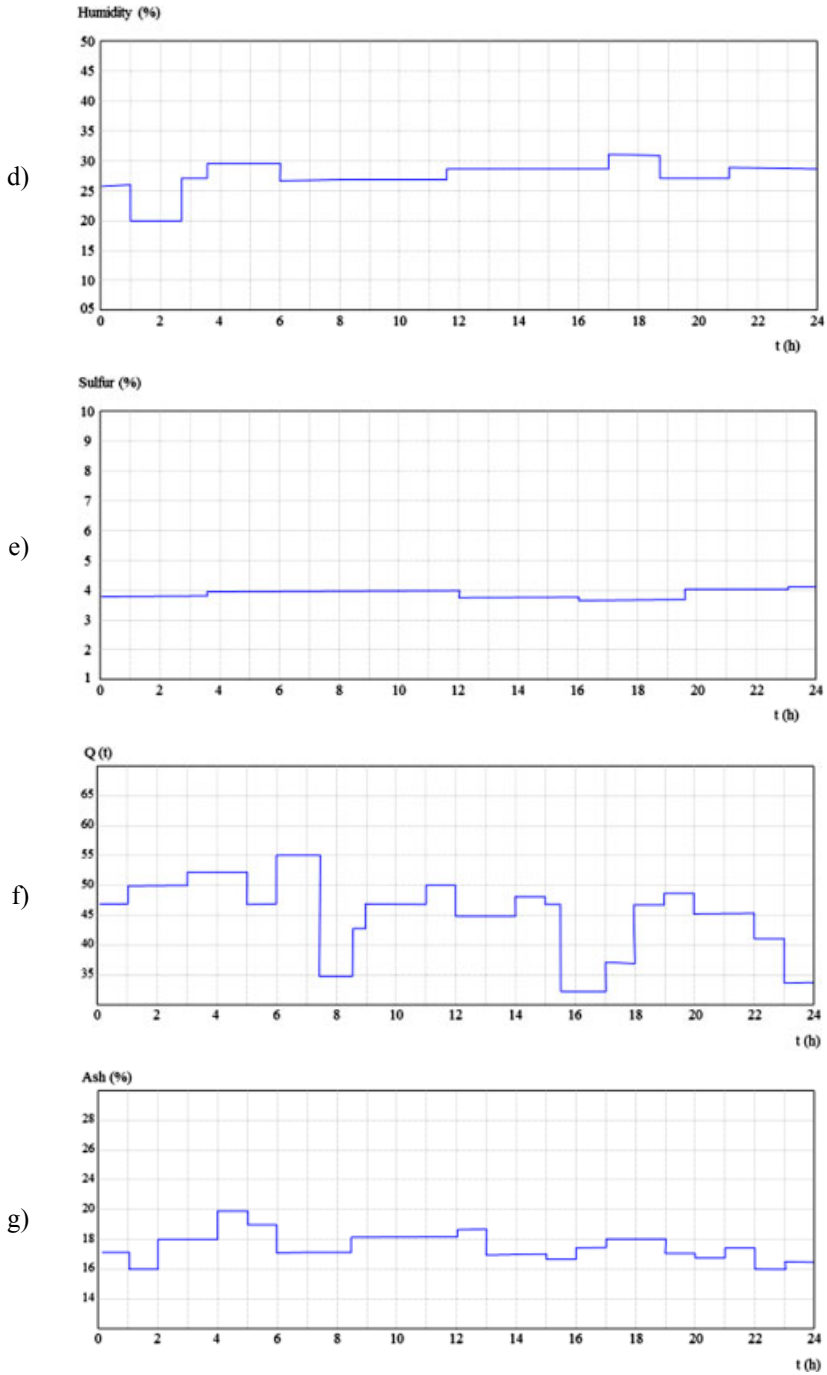
Fig. 8 continued. Part of the simulation tests results:
d) Run-of-mine coal humidity; e) Run-of-mine coal sulfur content; f) Plant production per hour;
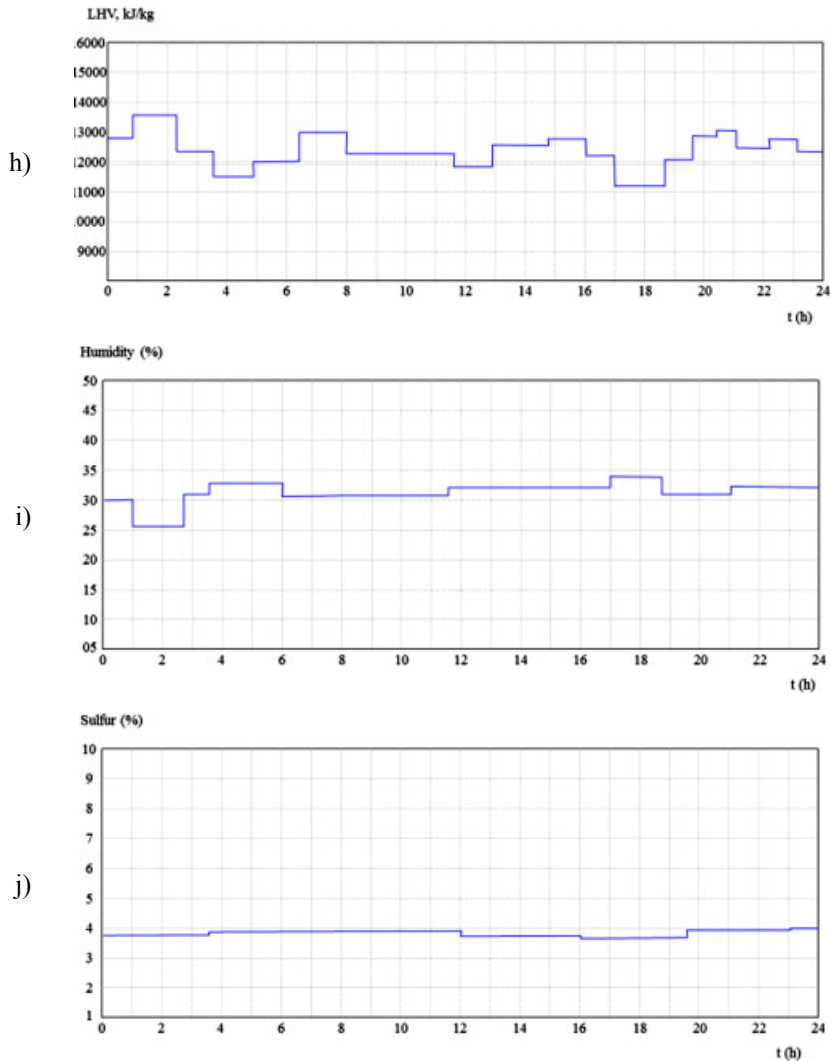g) Clean coal ash content

Fig. 8 continued. Part of the simulation tests results:
h) Clean coal Lower Heat Value; i) Clean coal humidity; j) Clean coal Sulfur content

the average discrepancy amounts to 6.75 (%), and the lowest discrepancies were observed with sulfur content (1%), and the highest with humidity content (11%).

This outcome of experimental tests of the developed fuzzy model for the process of autogenous suspension coal cleaning on the example of "Bogutovo selo" open pit mine is relying on the:

1. Reliability and the quality of input data;
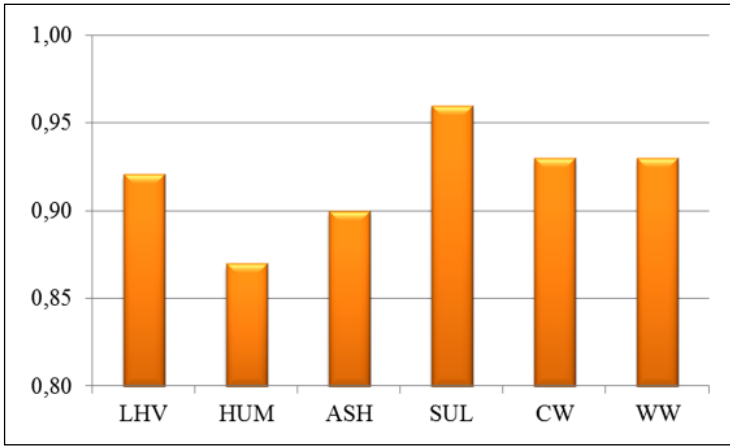2. Adequate process algorithm and the simulation model;
3. Correct fuzzyfication

Fig. 9. Correlation of model input and output parameters (ordinate: correlation coefficient value)
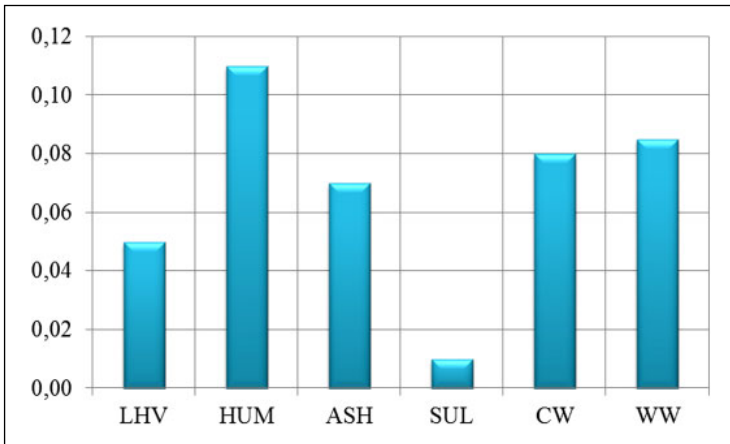

Fig. 10. Discrepancies of model and real process parameters (ordinate: discrepancy value, × 100%)

Without fulfilling all of the above examples, the model loses its reliability attribute. With changes of input parameters and the disturbances within regular operative boundaries, the model maintains the fast response, which recommends it equally as the efficient assisting model in the analysis and researching coal cleaning processes, and with bringing management decisions in extended or real time. In comparison with the deterministic models, fuzzy model advantages are: flexibility, easy and fast adaptability, lower complexity of the mathematical-modeling description of the real system and significantly lower sensibility regarding the input data discrepancies.

6. Conclusion

The presented fuzzy simulation model was developed on the example of the processing plant for cleaning of coal at the "Bogutovo selo" open pit mine of the Mine and Thermal Power Plant Ugljevik. Tests performed on the model presented confirm its practical applicability and reliability, reflecting in discrepancies between the model and the real process parameters within the limits of the allowed industrial error. The model can be successfully used in analytics, virtual experimental research, testing during the phase of design of coal cleaning plants and the logistics of monitoring-management systems in extended or the real time. The specifics of the coal cleaning system are reflecting in always possible surprises in production, logistics and accessory activities. This fact is recommending fuzzy logic as the suitable mathematical-modeling approach for modeling of this and the similar production systems, but the assumption of the successful fuzzy modeling approach for coal cleaning process means: reliability of input data, their adequate acquisition, fuzzy logic processing and the correct process algorithm.

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