



**University of Belgrade
Technical Faculty in Bor**



**Chamber of Commerce
and Industry of Serbia**

XV International Mineral Processing & Recycling Conference



Proceedings

Editors:
Jovica Sokolović
Milan Trumić

**17-19 May
2023**

**Belgrade
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TABLE OF CONTENTS

PLENARY LECTURES	1
L. Guo, Y. Zhao, Q. Ma, G. Tang, C. Jia, C. Li RESEARCH PROGRESS, TRENDS, AND INNOVATIONS OF DEVELOPMENT ON MINING BACKFILL TECHNOLOGY OF UNDERGROUND METALLIFEROUS MINE	3
V.A. Chanturia, V.V. Morozov, G.P. Dvoichenkova, E.L. Chanturia, Yu. A. Podkamenny INNOVATIVE TECHNOLOGY FOR THE RECOVERY OF ABNORMALLY LUMINESCENT DIAMONDS BASED ON THE USE OF LUMINOPHORE-CONTAINING MODIFIERS	23
G. Vujić N. Maoduš, M. Živančev WTE AS INTEGRATED PART OF CIRCULAR ECONOMY	32
J.C. Gabriel, H. Bo, N. Charpentier, S. Chevrier, Y. Deng, F.Olivier, D. Xia CRITICAL METALS RECOVERY FROM E-WASTE: FROM MICROFLUIDICS HYDROMETALLURGY TO ECONOMICALLY VIABLE PROCESSES	39
SESSION LECTURES	41
F. Nakhaei, I. Jovanović 3D IMAGING AND APPLICATIONS IN MINERAL PROCESSING	43
D. Singh, S. Basu, B. Mishra. R. Bhima Rao NOVEL APPROACHES TO RECOVER TOTAL HEAVY MINERALS FROM DIFFERENT GRADE BEACH SAND DEPOSITS USING GRAVITY CONCENTRATORS	54
M. Trumić, K. Balanović ROLE OF PARTICLE SHAPE IN THE FLOATABILITY OF TONER PARTICLE	64
I. Smičiklas, M. Egerić, M. Jović COPPER SORPTION CAPACITY OF THE SOIL TREATED WITH UNCONVENTIONAL ALKALIZING AGENTS	73
V. Conić, I. Jovanović COPPER ORE BIOLEACHING FROM ECOLOGICAL POINT OF VIEW	79
S. Cvetković, M. Popović, J. Perendija LIFE CYCLE ASSESSMENT AND USE OF NATURAL RESOURCES	89
WORKSHOP PAPERS	95
P. M. Angelopoulos, G. Anastassakis, N. Kountouris, N. Koukoulis, M. Taxiarchou COMBINED USE OF ORGANOSOLV LIGNIN AND XANTHATES ON SPHALERITE FLOTATION FROM MIXED SULPHIDES	97
P. M. Angelopoulos, N. Kountouris, G. Anastassakis, M. Taxiarchou PARTIAL REPLACEMENT OF XANTHATE BY ORGANOSOLV LIGNIN ON PYRITE/ARSENOPYRITE FLOTATION	103
K. Hrůzová, J. Ann Bazar, Leonidas Matsakas, Anders Sand, Ulrika Rova, Paul Christakopoulos ORGANOSOLV LIGNIN PARTICLES: A NOVEL GREEN REAGENT THAT INCREASES THE FLOTATION EFFICIENCY OF SULFIDE ORES	109
A. Peppas, D. Skenderas, P.M. Angelopoulos, C. Politi ENVIRONMENTAL BENEFITS OF LIGNIN BASED ECOFRIENDLY SURFACTANTS FOR FLOTATION PROCESSES TOWARDS CURRENT PRACTICES	115

A. Peppas, K. Hurzova, D. Skenderas, C. Politi, L. Matsakas, P.M. Angelopoulos EVALUATION OF BATTERY MINERALS FLOTATION PROCESS ECO FRIENDLINESS UTILISING BIODEGRADABLE LIGNIN REAGENTS	121
A. Peppas, C. Politi, D. Skenderas, P.M. Angelopoulos ENVIRONMENTAL ASSESSMENT OF RARE EARTHS RECOVERY METHOD FROM BAUXITE RESIDUES	126
PAPERS	133
A. Jankovic, M. Sederkennya MODIFIED BOND AND RITTINGER ENERGY-SIZE RELATIONSHIPS FOR LABORATORY FINE GRINDING	135
V. Nikolić, M. Trumić, D. Tanikić OPTIMIZATION OF MICRONIZING ZEOLITE GRINDING USING ARTIFICIAL NEURAL NETWORKS	143
E. Petrakis, K. Komnitsas THE EFFECT OF MICROWAVE RADIATION ON DRY GRINDING KINETICS OF BAUXITE ORE	150
M.H. Tyeb, S. Mishra, A.K. Majumder LSTM AND CNN COMBINATION BASED MODELLING APPROACH FOR PARTITION CURVE PREDICTION IN HYDROCYCLONES	157
I. Jovanović, M.Ž. Trumić, J. Sokolović, M.S. Trumić, J. Nešković DETERMINATION OF LIMITING SETTLING VELOCITY IN THE SLURRY PIPELINE FROM GRINDING PLANT, USING DIFFERENT APPROACHES – A CASE STUDY	163
N. Omarova, R. Sherembayeva, A.Amirkhan, Zh. Ibraybekov, A. Nesipbay FLOTATION OF POLYMETALLIC LEAD-ZINC ORES OF THE BAKALSKOYE DEPOSIT	168
V.A. Chanturiya, I.Zh. Bunin, M.V. Ryazantseva THE APPLICATION OF THE DIELECTRIC BARRIER DISCHARGE (DBD) FOR THE IMPROVEMENT OF THE SEPARATION OF PYRITE AND ARSENOPYRITE	174
V. Ignatkina, A. Kayumov, N. Yergesheva, P. Chernova BASIC SELECTIVE REAGENT REGIMES FOR COMPLEX SULFIDE ORE FLOTATION	179
S. Chaudhuri, S. Maity, S.C. Maji, D. Roy, U.S. Chattopadhyay STUDIES ON THE FLOATABILITY CHARACTERISTICS OF LOW VOLATILE COKING COAL FINES USING X-RAY DIFFRACTION (XRD) ANALYSIS AS A DIAGNOSTIC TOOL	186
V.I. Ryaboi, V.P. Kretov, E.D. Schepeta, I.V. Ryaboi, S.E. Levkovets APPLICATION OF COLLECTOR BTF-15221 IN FLOTATION OF COPPER- AND GOLD - CONTAINING ORES	193
I. Dervišević, A. Dervišević, M. Tomović, J. Galjak COMPARATIVE ANALYSIS OF REAGENTS FOR GOLD EXTRACTION FROM FLOTATION TAILS	202
E.M.S. Silva, A.C. Silva, J.M.B.S. Cabral, P.S. Oliveira, A.F. Nascimento, A.P. Vieira Filho, S.A. Santos TESTS WITH DIFFERENT FLOCCULANTS FOR CHROMIUM ORE TAILINGS	208
C. Ouyang, B. Lv, K. Jia, Y. Yang STUDY ON THE APPLICATION OF HIGH-EFFICIENCY AND ENVIRONMENT-FRIENDLY COPPER COLLECTOR TO ASSOCIATED COPPER IN AN IRON ORE	214
S. Sredić, Lj.Tankosić KINETIC STUDIES OF THE ADSORPTION POLYACRILAMIDE-BASED FLOCCULANTS ON NATURAL GOETHITE, QUARTZ AND CLAY MINERALS	221

G. D. Bogdanović, D. Marilović, B. Nikolić, S. J. Petrović COLUMN LEACHING OF LOW-GRADE COPPER SULFIDE ORE WITH SULFURIC ACID	230
K. Gáborová, M. Achimovičová, M. Hegedüs, O. Šestinová AN INFLUENCE OF MECHANICAL ACTIVATION ON THE COPPER LEACHING KINETICS OF BERZELIANITE	236
D. Medić, I. Đorđević, M. Nujkić, A. Papludis, V. Nedelkovski, S. Alagić, S. Milić USE OF COPPER POWDER AS A REDUCING AGENT IN THE LEACHING PROCESS OF LiCoO_2	242
J. Dimitrijević, S. Jevtić, A. Marinković, M. Simić, M. Koprivica, J. Petrović REMOVAL OF HEAVY METAL IONS FROM MULTIMETALLIC SOLUTION BY MODIFIED OAT STRAW	248
M.R. Rath, A.S. Patra, S. Kiran Kumar, M. Mukherjee, A. Chatterjee, A. Ranjan, A.K. Bhatnagar, A.K. Mukherjee A PROCESS TO DECREASE THE CLAY COATING OF IRON ORE LUMPS & FINES BY THE APPLICATION OF DISPERSANTS	254
H. Kurama, S. Kurama SURFACTANTS AND THEIR FUNCTIONS ON NANO-POWDER SYNTHESIS	262
A. Goryachev, D. Makarov METHODS FOR PROCESSING NATURAL AND ANTHROPOGENIC COPPER- NICKEL RAW MATERIALS IN THE ARCTIC	275
Y. Yuankun, D. Mirović DAM BREACH ANALYSIS USING HEC-RAS: A CASE STUDY OF COPPER AND GOLD "ČUKARU PEKI" MINE DAMS	283
A. Milovanović Brkić, Y. Yuankun, N. Buđelan MANAGEMENT OF FLOTATION TAILINGS AS MINING WASTE ON THE COPPER AND GOLD MINE "CUKARU PEKI"	289
N. Pavlovic, F. Palkovits, A. Hall GEO-STABLE DISPOSAL OF COAL COMBUSTION BYPRODUCTS	297
N. Pavlovic, F. Palkovits, A. Hall TAIL WAGGING THE DOG-WHY INTEGRATED SOLUTIONS ARE BETTER-TAILINGS AND BACKFILL DISPOSAL	303
V. Alivojvodic, N. Petrovnijevic POSITION OF COPPER WITHIN URBAN MINING - RECOVERING POTENTIAL FROM MINE TAILINGS	309
V.Tsitsishvili, N.Dolaberidze, N.Mirdzveli, M.Nijaradze, Z.Amiridze, B.Khutsishvili BACTERIOSTATIC ACTIVITY OF GEORGIAN HEULANDITE ENRICHED WITH BIOLOGICALLY ACTIVE METALS	315
V.Tsitsishvili, M.Panayotova, N.Dolaberidze, N.Mirdzveli, M.Nijaradze, Z.Amiridze, B.Khutsishvili, N.Jakipbekova, S.Sakibayeva THERMAL STABILITY OF NATURAL HEULANDITE-CHABAZITE MIXTURES	321
V.Tsitsishvili, M.Panayotova, N.Dolaberidze, N.Mirdzveli, M.Nijaradze, Z.Amiridze, B.Khutsishvili, N.Klarjeishvili, N.Jakipbekova COMPOSITION OF GEORGIAN AND KAZAKHSTANI NATURAL HEULANDITES	327
S. Matijašević, S. Grujić, V. Topalović, J. Stojanović, J. Nikolić, V. Savić, S. Zildžović NANOCRYSTALLIZATION OF POTASSIUM NIOBIUM GERMANATE GLASSES	333

A.C. Silva, E.M.S. Silva, P.S. Oliveira, A.F. Nascimento, A.P. Vieira Filho, D.B. Carvalho Neto ESTIMATING THE ACCURACY, PRECISION, AND RECALL OF THE HAND-SORTING OF A BRAZILIAN CHROMIUM ORE	338
V.V. Morozov, Y.P. Morozov, G. Zorigt, D. Lodoy, E. Jargalsaikhan, I.V. Pestriak SCANNING FLATBED OPTICAL ORE QUALITY ANALYZER	344
B. B. Tchouffa, N. J. Ndemou, M. G. Frida Ntsama CHARACTERIZATION, ENRICHMENT TEST AND VALORIZATION OF IRON ORE FROM NABEBA (NORTH – CONGO)	350
K. Jia, S. Đorđević, C. Ouyang, B. Lv LABORATORY BENEFICIATION TECHNOLOGY AND DEVELOPMENT RESEARCH ON TITANIUM MAGNETITE ORE	355
D. S. Radulović, V. Jovanović, B. Ivošević, D. Todorović, S. Milićević, M. Marković INVESTIGATION OF THE POSSIBILITY OF VALORIZATION OF TWO BORATE SAMPLES FROM THE DEPOSIT "POBRĐE" – BALJEVAC	361
S. Hredzák, M. Matik, O. Šestinová, A. Zubrik, D. Kupka, S. Dolinská, I. Znamenáčková, M. Sisol, M. Marcin, L. Pašek STUDY OF ORE SAMPLES FROM THE ZLATÉ HORY DEPOSIT (HRUBÝ JESENÍK Mts., SILESIA, CZECH REPUBLIC)	367
J. Sokolović, I. Ilić, D. Krstić COMPARISON OF THE RESULTS OF SEPARATION OF DIFFERENT COALS IN THE ANTHRACITE MINE "VRSKA CUKA"	373
B.R. Reddy, K. Abhishek, J.M. Korath, M.R Rath A COMPUTATIONAL TOOL FOR PREDICTION OF JIG CONCENTRATOR OPERATING PARAMETER TO GET IMPROVED YIELD OF CONCENTRATE	379
I. Jovanović, V. Conić, D. Milanović, F. Nakhaei, S. Krstić RELATIVE PREDICTION ERROR OF FLOTATION INDICES BY ANFIS MODELS	387
Z. Štirbanović, R. Stanojlović, J. Sokolović, D. Stanujkić, N. Čirić, I. Miljanović, G. Popović APPLICATION OF VIKOR METHOD FOR SELECTION OF COLLECTOR IN PORPHYRY COPPER ORE FLOTATION	391
S. Milutinović, Lj. Obradović, S. Petrović S. Magdalinović, I. Svrkota RANKING OF FLOTATION TAILINGS POND IN EASTERN SERBIA USING THE AHP METHOD	398
I. Jovanović, V. Conić, J. Sokolović, D. Kržanović, D. Radulović SIMPLE FUZZY MODELS FOR PREDICTION OF FLOTATION INDICES	404
S. Mishra, M.H. Tyeb, A.K. Majumder DEVELOPMENT OF A VIBRATION SENSOR-BASED ONLINE MONITORING SYSTEM FOR DETECTING ROPING IN HYDROCYCLONES	410
B. Farkaš, A. Hrastov, E. Orbanić THE IMPROVEMENT OF MINERAL PROCESSING – CASE STUDY	416
T. Mohit, P. Patel, P. Kaushal, J. Sahoo, V. Arumuru, B. Deo, M. Jain, R. Manchanda IMPROVED ON-LINE FAILURE PREDICTION METHOD OF COAL INJECTION SYSTEM USED IN A SPONGE IRON ROTARY KILN	423
M. Mikić, R. Rajković, S. Trujić, D. Kržanović, M. Jovanović IMPACT ON THE ENVIRONMENT AND OF THE OPEN MINE AND LANDFILLS IN SOUTH MINING DISTRICT – MAJDANPEK	429

M. Jovanović, D. Kržanović, R. Rajković, M. Mikić, M. Maksimović APPLICATION OF GEOGRIDS IN RECULTIVATION MEASURES AGAINST LAND DEGRADATION	435
V. Gardić, R. Marković, Z. Stevanović, A. Isvoran, T. Marković APPLICATION OF SUSTAINABLE CYCLING MANAGEMENT SYSTEM IN PHYTOREMEDIATION TECHNOLOGY OF CONTAMINATED SOILS	441
D. Đurđević-Milošević, A. Petrović, J. Elez, G. Gagula, V. Kalaba SUSTAINABLE APPROACH TO THE LACTIC ACID PRODUCTION AND ANTIBACTERIAL USE	445
B. Cekova, M. Matlievska, M. M. Puncheva, V. Velkoski, B. Kuzmanovski DIGITALIZATION OF WASTE, WAYS FOR MORE EFFICIENT WASTE MANAGEMENT	451
A. Vasileiadou, S. Zoras, A. Dimoudi INVESTIGATION OF SLAGGING CHARACTERISTICS OF INDUSTRIAL SOLID WASTES	458
A. Vasileiadou, S. Zoras, A. Dimoudi MODELLING OF CO _x AND NO _x EMISSIONS FROM INDUSTRIAL SOLID WASTES COMBUSTION USING ANSYS CHEMKIN PRO	464
Z. Bayer Ozturk, S. Kurama, A. Eser THE USAGE AND EFFECT OF BASALT CUTTING WASTE (BCW) IN CERAMIC GLAZE COMPOSITIONS CONTAINING OPAQUE AND MATT FRIT	470
D. Dinić, S. Stupar, N. Jovanović, M. Tanić, S. Jevtić SYNTHESIS AND CHARACTERIZATION OF POROUS CERAMICS BASED ON COPPER SLAG	480
M. Šišić, Dž. Dautbegović, M. Duraković ANALYSIS OF THE CHARACTERISTICS OF SLAG FROM METALLURGICAL PLANTS IN ZENICA DISPOSED OF INDUSTRIAL WASTE LANDFILL "RACA"	486
Dz. Datubegovic, M. Hasanbasic, M. Sisic, V. Birdahic ANALYSIS OF THE IMPACT OF THE INTRODUCTION OF LARGER CONTAINERS INTO THE WASTE COLLECTION SYSTEM IN THE CITY OF ZENICA	492
N. Bušatlić, I. Bušatlić, A. Halilović, N. Merdić, L. Kovač ENVIRONMENTALLY ACCEPTABLE CEMENTS WITH THE ADDITION OF GRANULATED BLAST FURNACE SLAG	498
A. Stojićević, M. Antić, M. Purić VEGETABLE INDUSTRY BY-PRODUCTS AS RAW MATERIALS IN FUNCTIONAL FOOD PRODUCTION	507
A. Petrović, R. Marković, D. Božić CARBON NANOTUBES AS POTENTIAL MATERIAL FOR WASTEWATER TREATMENT - A REVIEW	514
M. Marić, A. Ivković, B. Ivković, A. Janošević Ležaić, S. Uskoković-Marković, J. Savić, M. Milojević-Rakić, D. Bajuk-Bogdanović REMOVAL OF METHYLENE BLUE FROM AQUEOUS SOLUTIONS USING AN IRON-RICH SOIL	519
R. Marković, V. Gardić, R. Kovačević, Zoran Stevanović, A. Isvoran, V. Marjanović, A. Petrović BOR DISCRIT RIVERS WATERCOURSES CONTAMINATION BY Cu AND Ni IONS	524
P. Kekarjawlekar, N. Kamal, K. Maniyar, B. Deo, P. Nanda, P. Malakar, R. Manchanda DEVELOPING SAFE OPERATING PRACTICES (SOP) FOR POSTCOMBUSTION CHAMBER IN A SPONGE IRON PLANT	530

D. Milošević, M. Radosavljević, S. Polavder, Ž. Praštalo ARRANGEMENT OF FIELDS DEVASTATED BY CONSTRUCTION OF MAIN GAS PIPELINE	536
D. Đurđević-Milošević, A. Petrović, J. Elez, V. Kalaba, G. Gagula ENVIRONMENTAL PROTECTION THROUGH THE RATIONAL USE OF SODIUM HYPOCHLORITE AS A FUNGICIDE	542
G. Kyparissis, A. Goukoudis, G. Papadimas, E. Tasiopoulos, A. Vasileiadou CASE STUDY OF ENERGY SAVING IN A PUBLIC SCHOOL THROUGH THE INSTALLATION OF A PHOTOVOLTAIC SYSTEM ON THE ROOF	548
D. Topalović, J. Marković, M. Jović, S. Dragović, I. Smičiklas THE ARSENIC SORPTION CAPACITY OF DIFFERENT SERBIAN SOILS	554
F. Popescu, M. Zot, E.A. Laza USING SHERPA TOOL FOR ASSESSMENT OF EUROPEAN WATERBORNE TRANSPORT SECTOR IMPACT ON AIR QUALITY	560
A. Stojić, D. Tanikić, E. Požega THE IMPACT OF EXPLOITATION OF PRIMARY AND ALTERNATIVE ENERGY SOURCES ON THE ENVIRONMENT	566
A. Radojević, S. Šerbula, T. Kalinović, J. Milosavljević, J. Kalinović MOBILE PHONES – A VALUABLE COMPONENT OF E-WASTE STREAM	572
K. Janković, M. Stojanović, D. Bojović, A. Terzić, S. Stanković APPLICATION OF COAL COMBUSTION BYPRODUCTS IN SELF-COMPACTING CONCRETE: INFLUENCE ON FLOWABILITY	579
D. Radosavljević, A. Jelić, M. Stamenović IMPACT OF STUDENT MIGRATIONS ON SUSTAINABLE AND TECHNOLOGICAL DEVELOPMENTS OF THE REPUBLIC OF SERBIA	585
D. Radosavljević, A. Jelić, M. Stamenović DEVELOPMENT OF EDUCATION FOR SUSTAINABLE DEVELOPMENT AND MANAGEMENT OF RECYCLABLE WASTE IN THE REPUBLIC OF SERBIA	592
Deependra Singh SUSTAINABLE RECOVERY OF INDIAN PLACER MINERALS-THEIR DISTRIBUTION AND MINERAL ASSEMBLAGES	598
ABSTRACTS	607
M. Tasić, I. Stojković, V. Pavićević, V. Veljković SIMULATION OF HYDRODYNAMIC CAVITATION-ASSISTED BIODIESEL PRODUCTION FROM WASTE COOKING OIL USING ASPEN PLUS	609
A. Jocić, S. Marić, A. Dimitrijević RECOVERY OF METALS FROM INDUSTRIAL EFFLUENTS USING AN IONIC LIQUID-BASED STRATEGY	610
S. Marić, A. Jocić, A. Dimitrijević IONIC LIQUID-BASED TECHNOLOGY FOR METAL RECOVERY FROM ELECTRONIC WASTE	611
J. Vučićević, S. Čupić, M. Jauković, V. Đurđević, M. Stamenović, A. Božić, A. Janićijević CURRENT STATE OF THE QUALITY OF THE LUG RIVER IN THE MUNICIPALITY OF MLADENOVAC	612

D. Žnidarič THE ENERGY CRISIS AND THE EXPLOITATION OF MINERAL RESOURCES IN THE LIGHT OF INCREASING LOADS IN SPACE	613
S. Zeković A NEW GLOBAL CHALLENGES AND REGULATION FOR SUSTAINABLE SPATIAL DEVELOPMENT OF MINING	614
P.M. Angelopoulos, P. Oustadakis, G. Anastassakis, M. Georgiou, N. Kountouris HYDROTHERMAL TREATMENT OF BAUXITE RESIDUE FOR IRON RECOVERY ENHANCEMENT BY MAGNETIC SEPARATION	615
O. Ayoglu, M. Sinche-Gonzalez, M. Moilanen TEXTURAL MINERALOGICAL UNDERSTANDING OF MAGNETITE LIBERATION CONTAINING COPPER INCLUSIONS	616
M. Sinche-Gonzalez MASTER IN MINERAL PROCESING (EMJM-PROMISE) IN THE CONTEXT OF DEMAND OF CRITICAL MATERIALS AND ENERGY TRANSITION	617
ADVERTISING MATERIALS	619
Department for Mineral and Recycling Technologies	621
Serbia Zijin Mining	624
Serbia Zijin Copper	627
Analysis d.o.o.	629
tozero	631
Monicom	632
EMJM-PROMISE	633

SIMPLE FUZZY MODELS FOR PREDICTION OF FLOTATION INDICES

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ABSTRACT – This paper presents the development and validation of two simple copper flotation models based on fuzzy logic (Mamdani and Takagi-Sugeno fuzzy inference system). Given that the Cu flotation process contains a large number of variables (especially inputs), models are called simple, because they contain only three input and three output variables. Input variables are feed grade, collector consumption in the roughing stage and overall frother consumption. Output variables are final concentrate grade and recovery as well as final tailings grade. The training and evaluation of the proposed models were accomplished on the basis of real process data from the industrial flotation plant of “Veliki Krivelj Mine”. The results showed that the proposed fuzzy models well describe the behavior of the industrial flotation plant in a wide range of circumstances (correlation coefficient $R > 0.89$ in all cases). There is almost no difference between the results, whether Mamdani and Takagi Sugeno fuzzy inference system is applied.

Keywords: Fuzzy model, Flotation, Copper ore

INTRODUCTION

Many of the unit processes in mineral processing, (such as flotation) are multivariate systems and have nonlinear characteristics. Traditionally, they have been controlled using linear controllers such as proportional-integral-derivative (PID) controllers. These simple controllers are often acceptable if the process operation is restricted to a small region around the nominal operation point. Different control techniques should be used when high performance is required over a range of operation conditions. Fuzzy logic control is an alternative to realize nonlinear, multivariable control strategies [1].

For the purpose of the current research, the two most common FIS types were established: the Mamdani fuzzy inference system marked as EMM and the other based on the Takagi-Sugeno fuzzy inference system, marked as ESM. There are some differences between them.

The ESM model is made by the appropriate transformation of the EMM model. The output of the Takagi-Sugeno is linear or constant, but the output of Mamdani is the membership function. The final stage is the defuzzification in which the fuzzy results are translated to crisp form values [2].

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EXPERIMENTAL

Simple (Elementary) Fuzzy Logic Model based on Mamdani Inference System (EMM)

This model was developed using the Fuzzy Logic Toolbox program module, which serves to generate fuzzy logic reasoning systems. The model is called simple or elementary, because it contains only three input variables and, as a result, a base with a relatively small number of fuzzy rules.

The basic methodological features of the EMM model are: (1) Mamdani inference system; (2) application of the AND (minimum) fuzzy operator in all rules; (3) implication method – minimum; (4) aggregation method – maximum; (5) defuzzification method – centroid; (6) number of rules – 63.

The input variables in the model are feed grade (FCU), collector consumption in the rough flotation stage (PXR) and frother (FRT). Output variables are concentrate grade (CCU), tailings grade (TCU), and concentrate recovery (RCU). Other parameters were considered constant due to different reasons. More details about this model development are given in literature [3]. Figure 1 presents some of the resulting surfaces provided by the model.

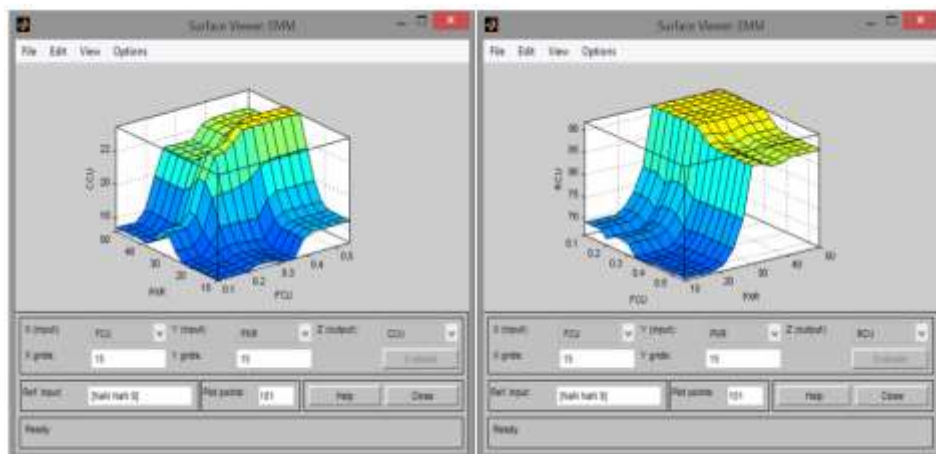


Figure 1 Resulting surfaces of the EMM model: left – dependence of the concentrate grade on the feed grade and collector consumption in roughing stage; right – dependence of copper recovery in the final concentrate on the feed grade and consumption in roughing stage

The resulting surfaces in Figure 1 show a logical sequence of cause-and-effect relationships between the considered variables. Namely, increasing the dose of the collector first leads to an increase, and then to a decrease in the grade of the concentrate, while the recovery of copper in the concentrate increases.

This shape of the resulting surfaces, indicates the adequacy of the fuzzy rules, given that the trends of the values of the dependent variables correspond to the real behavior of industrial flotation system.

Simple (Elementary) Fuzzy Logic Model based on Takagi-Sugeno Inference System (ESM)

The elementary Takagi-Sugeno model is formed by the appropriate transformation of the EMM model. Its main features are: (1) Takagi-Sugeno inference system; (2) application of the AND (minimum) fuzzy operator in all rules; (3) implication method – product; (4) aggregation method – sum; (5) defuzzification method – weighted average; (6) number of rules – 63. More details about this model development are given in literature [3]. Figure 2 shows resulting surfaces of the ESM model, respectively.

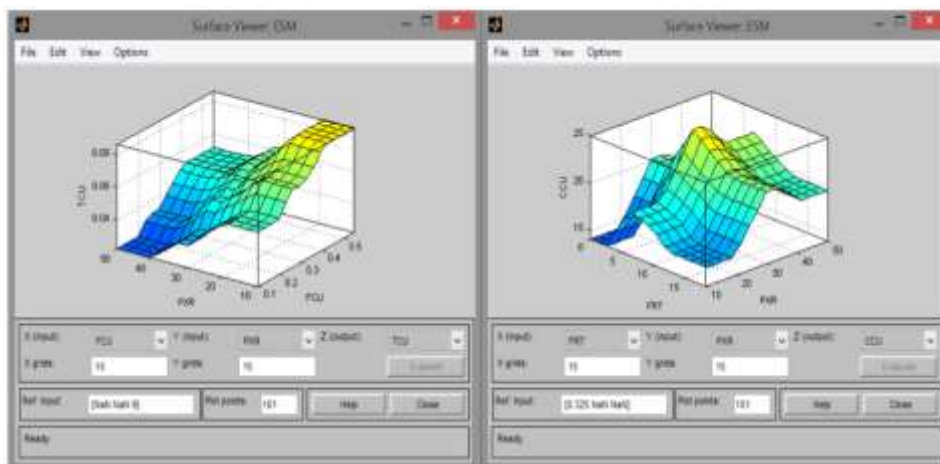


Figure 2 Resulting surfaces of the ESM model: left – dependence of tailings grade on copper content in the feed and collector consumption in roughing stage; right – dependence of the concentrate grade on the consumption of the collector in the roughing stage and the consumption of the frother

By observing the surfaces shown in Figure 2, it can be concluded that they represent the real process to a good extent. The copper content in the tailings increases with an increase of the copper content in the feed and decrease of the consumption of the collector, while a peak corresponding to the maximum grade of the concentrate can be observed on the surface on the right. This peak is coupled with the optimal consumptions of the collector and frother, which is also clearly visible in Figure 2.

RESULTS AND DISCUSSION

Evaluation of models was carried out in the MATLAB software package, by entering the real values of the input process variables from the industrial flotation plant "Veliki Krivelj" and generating the corresponding outputs predicted by the models. With the aim of determining the ability of each of the models to reliably predict the technological indicators of the flotation process based on the given input parameters, a regression analysis was performed in the Microsoft Excel program. As part of the regression analysis, the correlation between the real process values of recovery, concentrate grade and tailings grade with those obtained according to the models was considered.

Tables 1 and 2 show the results of the regression analysis for both models, while Figures 3 – 4 show their prediction errors of technological parameters. The prediction error (ε), which served as one of the criteria for evaluating the predictive properties of the model, was calculated according to the Formula (1):

$$\varepsilon = y_{pr} - y_{re} \quad (1)$$

Where:

y_{pr} – predicted value of flotation index

y_{re} – real value of flotation index

Table 1 Statistical analysis of actual and predicted values using the EMM model

Statistical parameters	Technological indices of the flotation process		
	Concentrate grade	Concentrate recovery	Tailings grade
Correlation coefficient R	0.98136	0.98943	0.89995
Determination coefficient R ²	0.96307	0.97896	0.80992
RMSE	3.87144	11.69683	0.03050

Table 2 Statistical analysis of actual and predicted values using the ESM model

Statistical parameters	Technological indices of the flotation process		
	Concentrate grade	Concentrate recovery	Tailings grade
Correlation coefficient R	0.98219	0.99537	0.90220
Determination coefficient R ²	0.96470	0.99077	0.81396
RMSE	3.98479	8.14911	0.02582

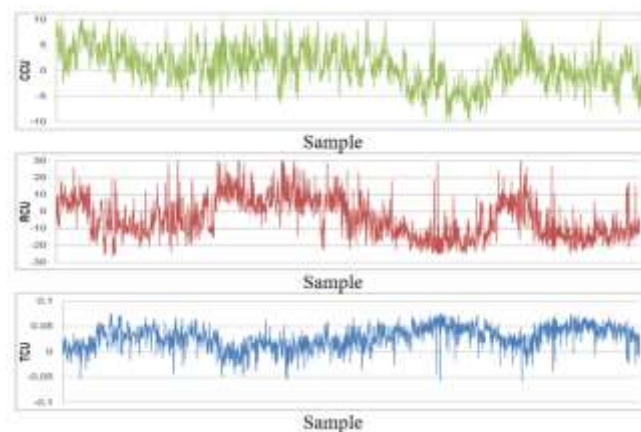


Figure 3 Prediction errors of technological indices according to the EMM model

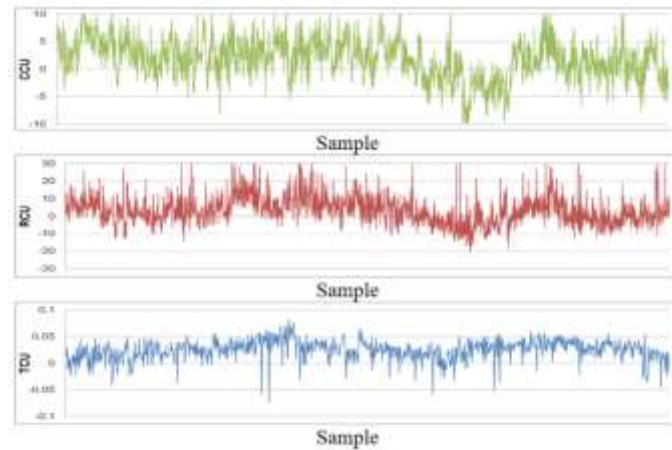


Figure 4 Prediction errors of technological indices according to the ESM model

By observing the trend of the prediction error of the concentrate grade, it can be concluded that the error mostly "oscillates" around the value of zero, which is expected. The only major deviation from this trend can be seen on the right half of the diagram, which, according to estimates, corresponds to the beginning of the last third of the observed time period of plant operation. In that period, prediction errors are mostly negative, which may indicate changes in the operating mode of the plant. These changes can be caused by various factors, which were not taken into account during modeling, such as, for example, changes in the fineness of grinding and/or regrinding due to the occurrence of softer or harder batches of ore, changes in the quality of the reagents themselves, etc. Furthermore, by looking at the trend of recovery error, it was observed that a positive recovery error (predicted values are higher than actual) is quite well followed by a negative tailings grade error. The reverse is also true – a negative recovery prediction error is followed by a positive tailings grade prediction error. Given that the recovery of copper in the concentrate and the content of copper in the tailings are in direct connection, this indicates a good general setting of the model, as well as the potential influence of process factors that were considered constant during the modeling. For the results obtained by the regression analysis of the ESM model, it can be stated that they are very similar to the results from the EMM model. Correlation coefficients are almost the same (about $R = 0.98$), as well as root mean square errors (RMSE is 3.87 and 3.98 for EMM and ESM, respectively). This points to the fact that in this case it does not make much difference whether the Mamdani or Takagi-Sugeno methodology was applied.

CONCLUSION

In this study, the metallurgical parameters of an industrial copper flotation plant were predicted by two fuzzy logic models (Mamdani and Takagi-Sugeno). The obtained correlation coefficients are very high, which generally indicates a good correlation between the actual and predicted values of the output variables. The significant deviations between actual and predicted values most likely occurred due to the

fluctuations in real process data that can be caused by various factors. By comparing the results of Mamdani and Takagi Sugeno fuzzy inference systems, it can be inferred that they demonstrate very similar predictive performance.

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