



**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
SERBIA**



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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.

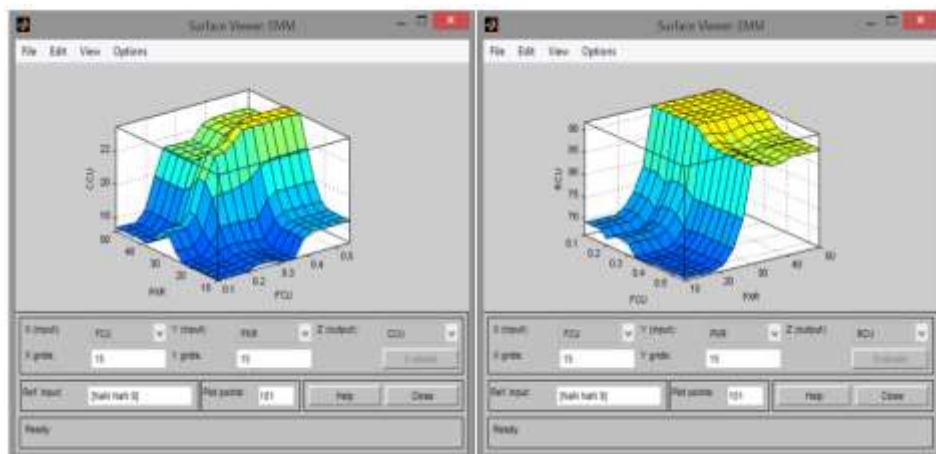


Figure 1 Resulting surfaces of the EMM model: left – dependence of the concentrate grade on the feed grade and collector consumption in roughing stage; right – dependence of copper recovery in the final concentrate on the feed grade and consumption in roughing stage

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.

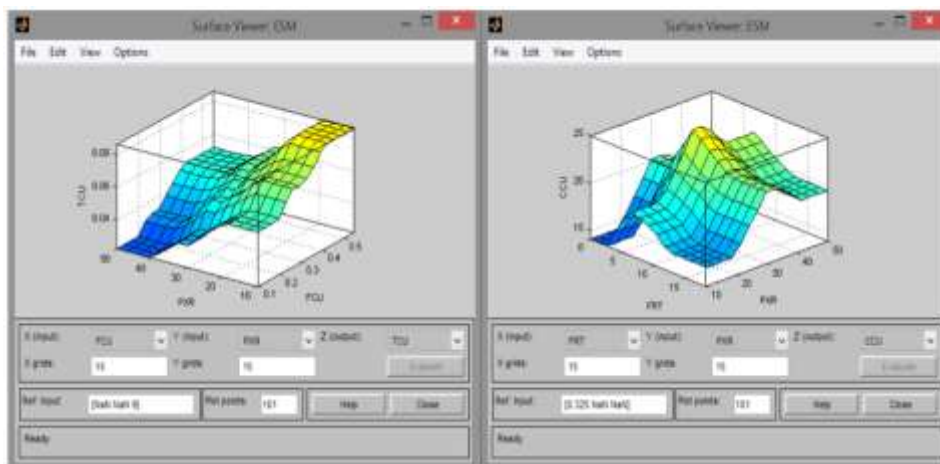


Figure 2 Resulting surfaces of the ESM model: left – dependence of tailings grade on copper content in the feed and collector consumption in roughing stage; right – dependence of the concentrate grade on the consumption of the collector in the roughing stage and the consumption of the frother

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

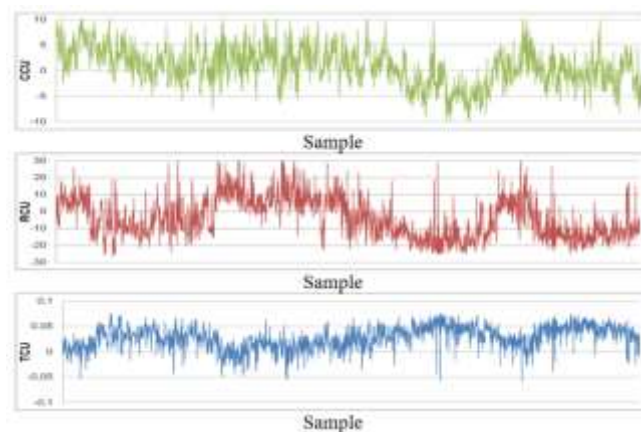


Figure 3 Prediction errors of technological indices according to the EMM model

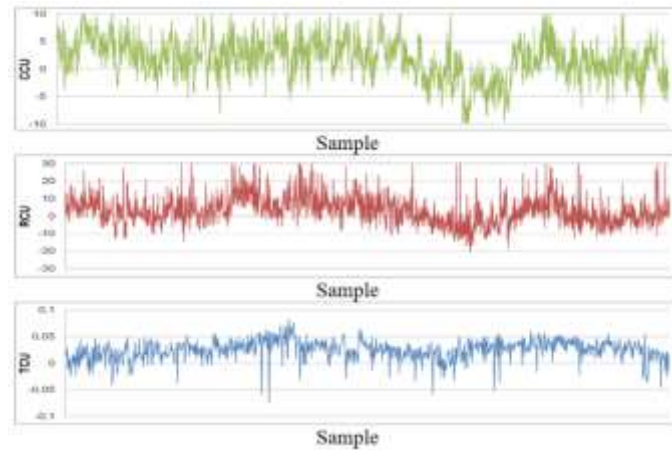


Figure 4 Prediction errors of technological indices according to the ESM model

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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