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Submission date: 23-Dec-2021 09:22AM (UTC+0700)
Submission ID: 1735161659
File name: MILLA_AIPCP_Article_update_trans.docx (171.56K)
Word count: 2907
Character count: 15491

Optimization Takagi Sugeno Kang Fuzzy System Using Mini-Batch Gradient Descent with Uniform Regularization

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Abstract. Interpreting vague shape into a logic statement is the function of fuzzy logic. Application of fuzzy logic has gone wide, and one of the proofs is fuzzy inference system. One of the methods in fuzzy inference system is Takagi Sugeno Kang fuzzy (TSK). The system construction of TSK fuzzy needs 2 main points, which is parameter identification and structure identification. System consequence in TSK fuzzy logic is not in the shape of fuzzy group but constant or linear equation. TSK fuzzy inference system that is optimized by using Gradient Descent shows a better performance while being operated. Mini Batch Gradient Descent (MBGD) is being used for renewing constant on gradient of the loss from several training in each iteration. Optimization using MGBD has been proven to solve large scale dataset by reducing the time and computation complexity. In this research, the method used is TSK with MGBD. The obtained rule the being optimized using modified MGBD by Uniform Regularization (UR). UR forces all rule to have an average firing level similar to input room, so that it has the same contribution in output. According to those rules, UR can increase the performance of generalization TSK fuzzy classifier. The purpose of this study is to observe the accuracy and classification using TSK with MGBD-UR. On this research, the data used is the data of air pollution in Jakarta using Indeks Standar Pencemar Udara (ISPU) that has been measured from 5 air quality monitoring station (SKPU) located in DKI Jakarta Province on April 2021 until July 2021. The data is being processed using Software Jupyter Notebook with Python programming language. The result of model evaluation using MAPE shows the overall error value is 23,16416%≈23%, which translates to the ability of prediction model is reasonable.

Keywords: Fuzzy, Optimization, Fuzzy System Inference, TSK, MBGD, UR

INTRODUCTION

The most important in classification is determining which criteria that will be used to make a decision in classifying things that want to be classified. Classification is a tool to group object classification with the basis of its characteristic in the shape of pattern, attribute, feature, and similar characteristic [1]. The goal of classification is to find a model that is able to predict the class of object which its label is still unknown [2].

Fuzzy logic can be used to solve the uncertainty or inaccuracy problem by applying concept, principle, and theory of fuzzy group through formulating several form of approximate logic [3]. One of the method used in fuzzy logic is IF-THEN rule. This kind of approach is easy to use because it develops model and algorithm that is closer with human's way of thinking [4].

Functions that can be used to represent fuzzy group are sigmoid, gaussian, and pi. In a more complex setting of computation, using triangle and trapezoid functions can make it easier to make a model of rule basis [5]. In the las several years, researchers have introduced a term called fuzzy type-1 as the synonym of Zadeh fuzzy group, which serves as a foundation in fuzzy group [6], [7].

Fuzzy system in a whole includes: fuzzification, inference, and defuzzification. Fuzzy inference is a process of taking conclusion from several fuzzy rules. Fuzzy inference system has a function of controlling the inference rules based on fuzzy logic [8]. One of developed fuzzy inference system Takagi Sugeno Kang fuzzy inference system [4].

The model of Takagi Sugeno Kang fuzzy logic (TSK) was introduced in 1985. As been known widely, TSK fuzzy logic can be classified into zero order, one order, even high order [9]. Similar with Mamdani fuzzy logic, where it forms an input-output relationship based on IF-THEN RULE with Max/Min method. The output in TSK fuzzy logic is not in the form of fuzzy group but in the form of constant or linier equation [10]. TSK fuzzy inference system that is being optimize using Gradient Descent shows a better performance when being operated [11].

Mini Batch Gradient Descent algorithm is a popular way to accelerate convergence and renew gradient constant with the amount of failure from the training example in each iteration. Optimization using MGBD has been proven to be able to handle large-scale dataset by reducing the computation complexity in each iteration and also reducing the complexity total of time for optimization [12]. It's a known fact that mini-batch gradient algorithm does not need certain exact value [13], [14].

Regularization technic is used to avoid overfitting and increase generalization. Regularization encourages algorithm by avoiding coefficient so that it's appropriate with training data sample [15]. In 2020, Yuqi Cui dkk [16] introducing a new term that is Uniform Regularization to exercise loss function in training TSK fuzzy classifier.

Data that is used is a data of air pollution in Jakarta in the form of Indeks Standar Pencemar Udara (ISPU) that is being measured in 5 different monitoring air quality station (SPKU) in DKI Jakarta Province on April 2021 – Juli 2021.

METODH

The method for this research is Takagi Sugeno Kang Fuzzy that has been optimized with Mini Batch Gradient Descent through Uniform Regularization. The details of the method is written as follows:

Fuzzy Group

Definition 1: If X is a group of objects that is symbolized as x, the fuzzy group U within X is expressed as sequence paired group,

$$U = \{(x, \mu_U(x) | x \in X\} \tag{1}$$

where $\mu_U(x)$ is a membership degree of fuzzy group U that is located in interval [0,1].

Fuzzy group may be represented in 2 notation, discrete and continuous. Fuzzy Group A in universe of discrete X, can be defined as:

$$A = \sum_{x \in X} \mu_U(x)/x \tag{2}$$

The symbol of $\sum$ doesn't represent the sum operation often used in mathematical setting, but as an aggregation operator that represent a group of membership value that is included in fuzzy group A. Fuzzy group A in continuous universe can be stated as:

$$A = \int_{x \in X} \mu_U(x)/x \tag{3}$$

The symbol of $\int$ doesn't represent integral operation but an aggregation operator.

Membership Function

Functions that can be used to represent fuzzy group are sigmoid, gaussian, and pi. There are several ways in forming membership function, where in this research the author used triangle curve membership function because it shows more optimal responds compared to the other type. [17].

$$\mu(x) = \begin{cases} \frac{(x-a)}{(b-a)} & a \leq x \leq b \\ \frac{(c-x)}{(c-b)} & b \leq x \leq c \\ 0 & others \end{cases} \quad (4)$$

Takagi Sugeno Kang

The rule formation is based on information extracted from expert or formed by using data. The consequence value of TSK is in the form of constant or linear equation. The rule sequence of fuzzy is written as follows:

$$IF\ (x_1\ is\ A_1)\cdot(x_2\ is\ A_2)\cdot(x_3\ is\ A_3)\cdot\ldots\cdot(x_N\ is\ A_N)\ THEN\ \ z = p_1{*}x_1+\cdots+p_N{*}x_N+q \quad (5)$$

With A_1 as fuzzy group i being antecedent, x_1 fuzzy group i as variable, p_1 is the consequence i, q is the strict constant as consequence, $\cdot$ as operator AND, and $i=1,2,\ldots,N$

If there is several rules, inference can be obtained from a group and correlation between rules. Method used in fuzzy inference system is MIN (Minimum). Results obtained will be used to modify fuzzy region and applies it to the output using fuzzy operator AND [18]. The shape of MIN operator can be written as follows:

$$\mu_{sf}[x_i] = MIN\ (\mu_{sf}[x_i], \mu_{kf}[x_i]); i = 1,2,\ldots,N \quad (6)$$

where $\mu_{sf}[x_i]$ is a fuzzy solution membership until rule i and $\mu_{kf}[x_i]$ is the value of consequence membership rule i.

Last step in TSK fuzzy inference system is defuzzification. Defuzzification result will be shown in real number that is strict and suitable for fuzzy logic system application. Defuzzification value (Z^*) in TSK can be found by calculating average centred value using the equation below:

$$Z^* = \frac{\sum_{i=1}^{N} a_i z_i}{\sum_{i=1}^{N} a_i}; i = 1,2,\ldots,N \quad (7)$$

where N is the amount of antecedent, a_i is the value of alfa-cut in rule i, and z_i is a membership degree output value in rule i.

Mini Batch Gradient Descent

Fuzzy inference system can be optimized using Mini Batch Gradient Descent to solve large scale dataset by reducing computation complexity in each iteration. The obtained rule from fuzzification process then be optimized with MBGD. While the renewing of parameter in each rule can be written as follows:

$$\theta_k = \theta_{k-1} - \alpha \frac{\partial L}{\partial \theta_{k-1}} \quad (8)$$

Where $\alpha > 0$ is a learning rate, $\frac{\partial L}{\partial \theta_k}$ is a gradient from loss function L.

Uniform Regularization

UR method forces the rule to have a similar average firing level, by minimalizing the loss. Loss function in UR can be added in loss function used in MGBD training from fuzzy classification. While the renewing of MGBF-UR parameter for each rule can be written as follows:

$$\mathcal{L} = \ell + \alpha\ell_2 + \lambda \sum_{n=1}^{n} \left(\frac{1}{N} \sum_{n=1}^{n} y_i\, prediction - y_i\, actual \right)^2 \qquad (9)$$

where ℓ is a cross-entropy loss with the function of softmax activation, ℓ_2 is a regularization method with $L2$, N is a total of training examples, α and λ is a trade-off parameter.

Mean Absolute Percentage Error

MAPE is used in this research to evaluate the performance of several prediction model. The better prediction model has a smaller MAPE value [19]. MAPE value can be determined using equation below:

$$MAPE = \frac{1}{n} \sum_{t=1}^{n} \left| \frac{y_i\, actual - y_i\, prediction}{y_i\, actual} \right| \times 100 \qquad (10)$$

where y_i $actual$ is a categorical value in the data, y_i $prediction$ is a defuzzification value, and n is a number of total data.

EXPERIMENTS AND RESULTS

The data used are data from ISPU in SKPU that is located in DKI Jakarta Province on April 2021 until July 2021. Variables used are pm10 (x_1), pm25 (x_2), co (x_3), o3 (x_4), and category value (y). The total number of data are 610. Data processing is being done by using Software Jupyter Notebook with Python programming language.

TABLE 1. Fuzzy number result

x_1	x_2	x_3	x_4	y
0.9600	0.9388	0	0.2034	0.3200
0.3600	0.4490	0	0.2712	0.1250
⋮	⋮	⋮	⋮	⋮
0.4898	0.6905	0.4000	0.8305	0.4082
0.3333	0.3333	0	0.5593	0.8000

TABLE 1 showed the processed data using fuzzy logic. The data then will be going through as input to know the air quality and the category as output, so the data are being grouped according to the range and fuzzy class.

TABLE 2. ISPU category for ambient air particulate according to national standard

Indeks standar Pencemaran Udara	**24 hours PM10 $\mu g/m^3$**	**24 hours SO2 $\mu g/m^3$**	**8 hours CO $\mu g/m^3$**	**1 hour O3 $\mu g/m^3$**	**24 hours PM25 $\mu g/m^3$**	**Category**
0-50	1-50	0-80	0-5	0-120	0-15	Good
51-100	51-150	81-365	6-10	121-235	16-65	Moderate
101-200	151-350	366-800	11-17	236-400	66-150	Unhealthy
201-300	351-420	801-1600	18-34	401-800	151-250	Extremely Unhealthy
>300	>421	>1601	>35	>801	>251	Danger

The TABLE 2 consisted of reference about value that is being used as standard in forming membership function for each data variable. These are the visualization of forming optimization in application of membership function fuzzy logic in air quality.

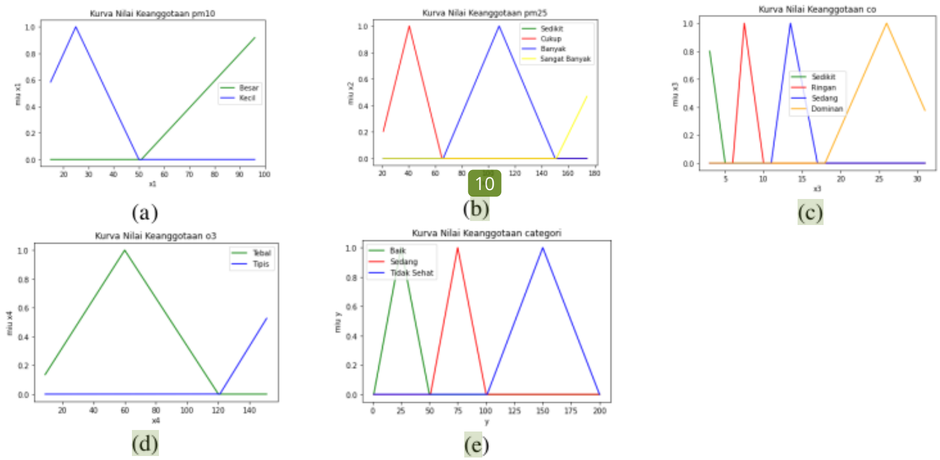

FIGURE 1. Figure (a), (b), (c), (d), and (e) is a representation of membership function from input and output variables

After going through a process of forming membership function using triangle membership function. The next step is to make rule and the rules obtained are being written as follows:

[R1] If X1 Big and X2 Abundant and X3 Moderate and X5 Thick so Y Moderate
[R2] If X1 Big and X2 Abundant and X3 Light and X5 Thick so Y Moderate
[R3] If X1 Big and X2 Abundant and X3 Moderate and X5 Thick so Y is Unhealthy
… … … … …
[R17] If X1 Big and X2 Abundant and X3 Little and X5 Thick so Y Unhealthy
[R18] If X1 Small and X2 Enough and X3 Little and X5 Thick so Y Good

On this research, the author used TSK fuzzy inference so the consequence value need to be changed to linear equation. If there are several rules, the inference is obtained from a group and correlation between rules. The method used in fuzzy inference system is MAX (Maximum) [20]. Next, there needs to be an optimization for each rule using MBGD-UR and the results are.

[R1] $Z^* = -0.12952 + 1.24341x_1 + 0.87695x_2 + 0.491287x_3 + 0.626108x_4$
[R2] $Z^* = 0.237397 + 0.1035x_1 + 0.288664x_2 + 0.18461x_3 + 0.109593x_4$
[R3] $Z^* = -0.12783 + 0.00876x_1 + 0.8761259x_2 - 0.07628x_3 + 0.285367x_4$
… … … … …
[R17] $Z^* = -0.22628 + 0.072821x_1 + 0.703393x_2 + 0.84602x_3 + 0.283367x_4$
[R18] $Z^* = -0.23006 + 0.60721x_1 + 0.379472x_2 + 0.048679x_3 + 0.236113x_4$

The output that is linear equation then being used to count the result of defuzzification. The defuzzification then will be compared with real data, which is shown in TABLE 3.

TABLE 3. ISPU category for ambient air particulate based on national standard

Defuzzification	Data
50.78716	42
68.60941	54
51.11017	42
96.44186	78
⋮	⋮
145.46	121
97.67458	80

According to TABLE 3, the calculation of MAPE can be written as follows:

$$MAPE = \frac{1}{607}\left(\left|\frac{42-50.78716}{42}\right| + \left|\frac{54-68.60941}{54}\right| + \cdots + \left|\frac{80-97.67458}{80}\right|\right) \times 100 = 23.16416\%$$

By MAPE calculation, it is obtained the overall error value which is 23.16416%≈23%, the value means that the ability of prediction model is reasonable.

According to defuzzification in TABLE 3 that is obtained through TSK MBGD-UR inference fuzzy system shows a rather relevant and stable value. The evaluation process that is being done by calculating error between defuzzification value and real data value shows that there is no far difference between the two. The visualization between defuzzification value and real data value is shown in FIGURE 2.

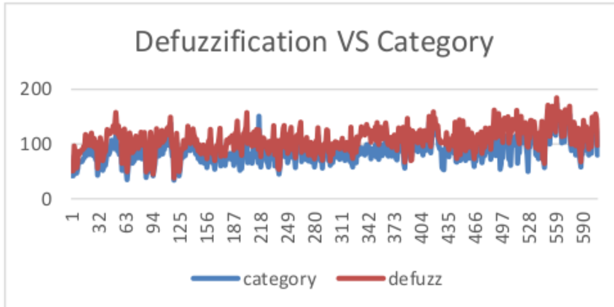

FIGURE 2. A graph between defuzzification value and data category

CONCLUSION

This research presents an explanation of application in Takagi Sugeno Kang inference fuzzy system that has been optimized with Mini Batch Gradient Descent with Uniform Regularization. The obtained rule value then optimized with the help of Mini Batch Gradient Descent with Uniform Regularization. The result showed the value of MAPE is 23% that explains the result is a normal occurrence. In another research, another method of optimization can be used in each rule.

ACKNOWLEDGMENTS

A gratitude presented for the head of math laboratory for its unending support in the form of numerous facilities so that it is possible for the author to finish the paper.

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