Development of control system for a complex technological object using fuzzy behavior charts

A. Bazhanov, R. Vashchenko, V. Rubanov

ARTICLE INFO

Keywords:
Industrial engineering
Membership functions
Technological node
Automated control system
Technological conditions
Technological process model
Fuzzy behavior chart

ABSTRACT

The cement kiln, which is the basic control object of the represented work, is the most power consumption unit of the cement production. The wet production method provides a better quality of output clinker in northern countries because of raw sources, which are already wet, and characteristics of Portland cement. However, there is one big problem standing against efficiency and concurrence with dry or semi-dry methods, there are no modeling algorithms and automated control systems for such an object. The overall control is available only with considerable time delays and operator handle support and some local control loops. There is proposed an original approach to dynamic processes modeling based on second rank fuzzy behavior charts, which is a basis of system control development for complex technological objects. The authors describe the application of control system development method based on fuzzy behavior charts during an advising control system construction for a wet method rotating cement kiln. During the development of the developed automated system was revealed a positive effect from the advising system implementation expressed in the increasing output of finished product with equal quality. The obtained data basis supports the conclusion that the application of the proposed method of developing control systems based on fuzzy behavior charts also possible for other complex technological objects.

1. Introduction

The relevance of the research is confirmed by the analysis of periodicals, which allows the conclusion that the automation issue remains unsolved for a number of production processes that have a control object with multiple interconnections of parameters. Moreover, the production process parameters are high delay, analog, controls, and analog controls. The current work focuses on the clear behavior charts method, which had been used for automation the chemical industry plants for example production of maleic anhydride. The construction of logical models for chemical technological objects (primary and source models) is described by prof. V.Z. Magergut, prof. S.A. Yuditsky, and prof. V.L. Perov in their work “The construction of logical models for chemical technological objects (primary and source models)”. However, the basic work applications were limited because of determining the object dynamics through the differential equations, which could describe its behavior on the clear section of the technological value changing range. Furthermore, such a method could give much efficiency because of prediction some abnormal and alarm modes by construction the model based on interconnected behavior charts and their sweeps in the form of marked Petri net. This article describes the presented method extension for more complex and therefore hard for automation production. The range of such objects, which require previous adequate modeling, is very large because of today materials production complexity. Many of them are soft non-formalized objects which work is described by human manner computing and furthermore, they have multiple interrelations between technological values, which can be fuzzy initially.

For making an adequate prediction of such an object dynamics there was taken the original method with implementation the fuzziness in the core of it. There is a possibility for the decision making of future object control by taking into account the predicted behavior and having the chart where we can catch the right control way from the directly actual state or that is more important the wrong control way, which could lead to the alarm state. Therefore, the fuzzy interpretation of the behavior chart could give us a powerful method for complex object dynamics analyses.

All research and development part was made on the basis of the first cement rotating kiln of the CJSC “Oskolcement”, located in Stary Oskol, Russian Federation. The statistical information was obtained for a period of five years and separated by three months periods for correlation estimation between fuzzy control system decisions and the really made control. During the automated control systems development, the mathematical model of the control object is the source. Depending on the tasks...
complexity level, which assigned to the system, mathematical models differ by the detail level, the presentation form as well as the information breadth about the controlled object state.

To initiate the presented approach development there was made a deep search of models or modeling methods, which could give the most complete description of the object and get the essential data of its operation, abnormal and alarm situations without clear behavior notation in the form of differential equations or with more adequate its interpretation. So the following results and its discussion could be made.

Article [1] provides a method of the mathematical model development of the aluminum hydroxide and Portland cement production processes in tubular rotary kilns. The model includes the differential equations system, which is a boundary value problem with boundary conditions set at different ends of the integration interval. At the same time, the author declares a number of significant simplifications in solving these equations and controlling the burning process using the obtained results.

The research [2] relates to the mathematical modeling of burning and heat exchange in a cement rotary kiln in the form of partial differential equations. To solve the control problems of the technological process with distributed parameters, it is necessary to develop a mathematical model that makes it possible to calculate the dynamics of space-time process parameters. However, the development of such a model in the form of differential equations has considerable challenges, since the analytical solution methods for this class problem are developed for a rather limited range of partial differential equations and, as a rule, the research of systems with distributed parameters is associated with using the appropriate computational methods. Moreover, the accuracy of the numerical solution compliance depends on the specific finite-differential scheme and the steps of sampling the modeling time and spatial variables. In addition, a significant challenge of such a numerical approach to the dynamics calculating problem of systems with distributed parameters is the sustainability assessment for space-time sampling of a finite-difference scheme, which like accuracy will depend on the sampling steps choice.

In the papers [3, 4] the authors suggest designing the control systems based on the joint application of fuzzy function theory and a new method of expert selection among working technologists-operators to fill in the knowledge base of associative data. The suggested approach to the development of intelligent automatic control systems of material burning processes in high-power rotary kilns is aimed at control accuracy and equipment productivity increasing due to the anticipatory detection of lining defects, which indicates a partial using of object parameters.

There is declared in [5] that in order to develop the models of chemical-technological objects the most effective approach is to create the deterministic models of an object using hydro-aerodynamics and the chemical reactions kinetics. The standard models are used as hydromodynamic ones. The proposed kinetic model of the process includes five chemical stages and one mass-exchange stage. Although the obtained models permit solving the problem of the temperature profile determination, based on which the maintenance of the optimal burning process is proposed, however, the completeness of the information is not sufficient for an integrated control system development.

The paper [6] presents an advisory system for a cement rotary kiln control, the algorithm of which has been developed on the basis of fuzzy set theory. It is proposed the kiln division into the several technological parts (zones) and has been determined the control actions according to the state vector of these parts. In addition, there is developed a control algorithm for the thermal technology apparatus and estimated the unit thermal state. It should be noted that during the development of this control system, the authors introduced the restrictions on the range of control parameters. Thus, the possibilities of the developed control system have been significantly reduced.

The following periodicals [7, 8, 9, 10] cover the range of various methods and approaches for complex technological object automation. The usage of classical mathematical techniques has been reviewed in several papers [11, 12, 13, 14, 15, 16].

The simulation of the control object (a rotary kiln) using one-dimensional model including the model of material layer height changing and the chemical reactions model is performed in [12, 13]. The work [11] also concerns a one-dimensional stationary model obtaining. In both cases, the authors take a number of assumptions in order to implement the developed models, which leads to a significant simplification of the kiln unit model and makes this approach unacceptable due to the crude of representation.

Papers [14, 16] describe the experimental research on mathematical modeling and the development of statistical and algebraic models of clinker burning technological process. There is the mathematical model of the kiln temperature profile in the form of partial differential equations offered in [15]. These classical mathematical models are applied for rotating “dry” kilns and the expediency of their usage is confirmed by experimental data. A significant non-stationarity of parameters during the “wet method” kiln operating does not allow to use the classical approach for it as a distributed object with the compilation of partial differential equations since there is a difficulty in the application of the known control system synthesis methods.

It is necessary to draw special attention to the works [17, 18, 19, 20, 21, 22, 23, 24, 25, 26], which are aimed at control system development based on fuzzy logic and neural networks methods, which are the point to the development of alternative control methods for cement kilns and provided an opportunity to consider them in the described research.

The usage of a neural network for a rotary kiln control system is considered in [25]. There is presented the neural network structure covers only a few circuits – pressure control and sintering zone control. The paper [22] proposes an adaptive neuro-fuzzy controller for a rotary kiln, which is successfully used in real production conditions on “dry” kilns. The monitoring system in [18] based on fuzzy logic proposes to control only a few process variables – the temperature in the sintering zone, the oxygen content in the exhaust gases and the outlet material temperature. Papers [20, 23, 24] describe the developed models on the basis of Mamdani and Sugeno fuzzy inference algorithms and [26] considers the development of an expert system and a fuzzy control system for clinker cooling. The article [21] also concerns the intelligent process control, which proposes a control approach to the unit for raw mix calcination based on fuzzy logic.

There are many sources report about the systems development for production process analysis using machine vision, in particular, the works [27, 28]. Several articles involve research based on the creation of remote control systems [29] and the development of expert systems based on Siemens PCS7 [30].

As could be seen, the automation problem for a number of production processes that have a control object with multiple interconnections and distributed parameters, a high delay and analog control bodies still remains unsolved. The nonstationarity and complexity of the physico-chemical processes occurring in such objects, a large number of external disturbances, the mutual influence of technological variables and parameters on each other do not allow the research and modeling using standard mathematical methods.

In order to make detailed overall processes analysis of such objects, there is proposed the method of control system development for complex technological processes based on fuzzy behavior charts of nodes. The essential point of this approach is to replace the continuous technological variable behavior with its discrete representation in the form of modes reflecting the general nature of this variable transient process in an object. Such an approach involves the research of technological processes “from the bottom” and development of models for its implementation in the form of fuzzy behavior charts of nodes (Figure 1), which are the basis for an automated control system development.

The model in the form of fuzzy behavior charts of nodes contains all the necessary information about technological variable behavior and makes it possible to take into account the additional information about possible situations, including abnormal and emergency ones, which increases the reliability of the developed system.
2. Main part

2.1. Modeling method

The method of automated control system development by complex technological processes is based on the original model representation of the control object in the form of fuzzy behavior charts of the nodes. Its main stages involve the following actions [31, 32]:

1. The apparatus external communication scheme development.
2. Object decomposition into nodes.
3. The description of the object technological variables.
4. The technological conditions (TC) description.
5. The development of fuzzy behavior chart of the node.
6. The arc marks description.
7. The technological nodes sweep obtaining.
8. The analysis of the technological nodes sweeps set.
9. The control automaton synthesis.

A fuzzy behavior diagram of the first rank [32] (Figure 1, a) is a base of the model. The term “rank” is used to define the term “mode”. The K-th rank mode of the technological variable $\sigma_i$ is the pair $(\Sigma_\sigma, \delta_i^\sigma)$ [sigma, delta], which determines the transition pattern of $\sigma_i$ [sigma] on the $\Sigma_\sigma$ [sigma] change segment by setting the K-th rank vector $\delta_i^\sigma(S_1^\sigma, ..., S_k^\sigma)$ [delta] of the derivative change in this segment, where $S_k^\sigma$ the characteristic of the K-th order derivative of variable $\sigma_i$ [sigma] as the time function, which taking three values: $S_k^\sigma = 0, S_k^\sigma > 0, S_k^\sigma < 0$.

The base model properties expansion [33] is performed by the introduction of the second rank fuzzy behavior chart, which allows taking into account not only the fact of the node behavior change but also the changing form by determining the signs of the first and the second derivatives (Figure 1, b).

A fundamentally new node model requires the change of the membership functions for technological variables used for fuzzy behavior charts of the first rank, as the number of positions on the fuzzy behavior chart of the second rank is added. Therefore, the membership function with three terms “minimum”, “norm” and “maximum” becomes incorrect. The correct solution is using the membership functions with five terms, where the terms “below norm” and “above norm” are additionally introduced. This terms number allow increasing the accuracy of the node model operating in general.

Thus, there should be used the trapezoidal membership functions for static modes and triangular membership functions for dynamic modes on fuzzy charts of the second rank (Figure 2).

After changing the node model as a fuzzy behavior chart, its model in a sweep form changes in its turn. A node sweep is a record of transition orders from one operating mode to another as the regular change sequence of the technological process and possible occurrences of abnormal situations.

On the generated membership functions basis, there are formed the conditions for disturbing factors and control actions, which determine the affiliation to a corresponding term:

\[
\begin{align*}
\theta_11 &= \begin{cases} 
1 - \text{if } T^h > T_k^h,  \\
0 - \text{if } T_k^h < T^h < T_n^h,  \\
0 - \text{otherwise;}
\end{cases} \\
\theta_12 &= \begin{cases} 
1 - \text{if } T^h = T_n^h,  \\
0 - \text{if } T_n^h < T^h < T_k^h,  \\
0 - \text{otherwise;}
\end{cases} \\
\theta_13 &= \begin{cases} 
1 - \text{if } T^h = T_k^h,  \\
0 - \text{otherwise;}
\end{cases} \\
\theta_21 &= \begin{cases} 
1 - \text{if } H^h = H_M^h,  \\
0 - \text{if } H_M^h < H^h < H_N^h,  \\
0 - \text{otherwise;}
\end{cases} \\
\theta_22 &= \begin{cases} 
1 - \text{if } H^h = H_N^h,  \\
0 - \text{if } H_N^h < H^h < H_M^h,  \\
0 - \text{otherwise.}
\end{cases}
\end{align*}
\]

where $T_k$ is the finished clinker temperature at the grate cooler outlet (°C); low ($T^h_0$), medium ($T^h_1$), high ($T^h_2$), $H_k$ – clinker layer height $H_k$ (cm); low ($H^h_1$), medium ($H^h_2$), high ($H^h_3$).

In addition to disturbance factors and control actions, the node operating is determined by the so-called technological conditions, which cause a change of the technological variable mode while constant control actions or retention the operating mode while changing the control actions [34]. The technological conditions could be written in the following form:

\[
\begin{align*}
\delta_1 &= \begin{cases} 
1 - \text{if the aspiration exhauster drive is in order } (F_a),  \\
0 - \text{otherwise,}
\end{cases} \\
\delta_2 &= \begin{cases} 
1 - \text{if the grates are in order } (F_g),  \\
0 - \text{otherwise.}
\end{cases}
\end{align*}
\]

The combination of disturbing factors, control actions, and
technological conditions form a single technological structure of the selected node (Figure 3) that is a basis for developing the model in the form of fuzzy behavior chart of the second rank (see Figure 1,b). Each vertex in this chart contains the following information: the position index number on the left separated side, the segment of the output technological variable change is above the horizontal line (here “The aspiration air temperature”) and the signs of the first and the second derivatives are under the horizontal line.

The arcs of the chart are marked by the mode changing conditions that are the rules of transition from one vertex to another. Such rules are Boolean functions that are composed of a specific set of perturbing factors, technological conditions and control actions. At that, there is only one transition between two vertexes (positions). This is the so-called condition of consistency (orthogonality) and it determines the correctness of the composed transition rules.

The transition conditions $f_i$ can be represented as follows:

$$f_0 = C \lor (Q_1 \lor ((\theta_{11} \land \theta_{21}) \land (\zeta_x \land \zeta_y)));
$$

$$f_1 = Q_1 \land ((\theta_{12} \land \theta_{21}) \land (\theta_{12} \land \theta_{22}) \land (\theta_{13} \land \theta_{23}) \land (1 \land (\zeta_x \lor \zeta_y) \land (\zeta_x \lor \zeta_y)))) .$$

The resulting node model in the form of fuzzy behavior chart of the second rank reflects all possible variants of its behavior and the change of technological variable operation modes.

Since the implementation of the joint operation algorithm of nodes consists of obtaining the production rules that allow the control system to determine the mode and evaluate the technological process state, a dimension problem arises because the output of each node contains the information about at least five operation modes of the technological variable changing model [35] (Figure 4).

This problem is solved by the aggregation of models presented in the form of fuzzy behavior charts that is an equivalent transformation into enlarged models, the validity of which is the consequence of process interconnections within the kiln unit. If the output technological variable $\sigma_1 \sigma_2$ of the node $U_{\sigma_1}$ is the disturbing factor (g3) for another output technological variable $\sigma_2 \sigma_3$ of the node $U_{\sigma_2}$ then there should be constructed the interaction scheme in the form of a serial connection of two nodes $U_{\sigma_1}$ and $U_{\sigma_2}$. As shown, instead of two output positions $P_1$ and $P_2$ there is one output position $P_2$, which contains all the necessary information about two nodes $U_{\sigma_1}$ and $U_{\sigma_2}$.

The model of the technological process is based on the developed node models taking into account the identified interconnections (Figure 5).

The structure of the control system (Figure 6) is developed in accordance with the used complex technical means on the research object – a rotary kiln and based on fuzzy behavior charts. The following notation is used: $Q$ – sludge consumption, $\tau$ – rotation period, $H$ – material height, $L$ – sintering zone length, $I$ – current of main drive load, $Q$ –...
- aspiration volume, $Q_{aga}$ – underestimate air volume, $Q_{ofa}$ – overfire air volume, $P_{he}$ – pressure in hot-end, $P_{kh}$ – pressure in kiln hood, $Q_{g}$ – gas consumption, $D_{cs}$ – chain screen wear, $T_{ph}$ – preheat zone temperature, $N_{dh}$ – number of double strokes the grate, $Gran$ – granulometric parameter, $T_{sa}$ – secondary air temperature, $H_{c}$ – height of clinker in cooler, $T_{cl}$ – clinker temperature, $T_{eg}$ – exhaust gas temperature, $T_{msz}$ – temperature of material in sintering zone, $C_{CO2}$ – carbon dioxide concentration, $C_{O2}$ – oxygen concentration, $T_{aa}$ – aspiration air temperature, $ChC$ – chemical composition.

2.2. Method implementation

Object-oriented programming (OOP) has been chosen as the main approach during program development. OOP has a number of advantages over procedural programming and allows to reduce the time of source code development, but it is worth noting that the use of this approach always assumes the greater role of preliminary design and the application domain analysis.

For this objective, there was created the universal software that suggests the possibility to implement the developed control algorithm. The software tool provides the ability to change the number of process variables (nodes), which allows the flexible adjustment of a unified process model and, accordingly, obtaining higher accuracy rates. In addition, it implements the editing of selected node models in order to adjust the membership functions of disturbing technological variables, control actions and transition rules for a fuzzy behavior chart. The need to adjust the model parameters is required either at the change of technological process operating conditions or control object, in particular when software could be used on another object.

To move a mark correctly along a fuzzy behavior chart of node, a number of procedures and functions have been implemented which performs the input of variables: name and value, the development of membership functions for linguistic variable terms, the determination of the range to which the technological value belongs, the verification of condition validity for transition operation. The structure of the logical unit is shown in Figure 7.
2.3. Software realization description

There are several features implemented in the developer window which are shown in Figure 9. Since the developed algorithms suppose their use on different objects, it is necessary to have the possibility of varying the number of technological variables (nodes) models and to edit them. The node could be edited immediately after its creation by setting: the names of the disturbing technological variables, control technological conditions and their values either manually or specifying a database link for an automatic update. The next step is the initializing data enter of the membership functions for each perturbing technological variable. The application provides a special window to entering and changing the transition rules, which also ensure the track of the rules operation correctness and the value that is assigned depending on the model operation.

The “System Operation Result” form (Figure 10) contains various information about the technological process course. The graphs show the status of each node. Besides, the text fields display information about the individual nodes operation modes and the control object operation mode as a whole. The text box displays advices to the operator about the necessary actions to stabilize the operation mode.

2.4. Comparison with other models

When the modeling of cement kiln work was started, we have faced with very low information about methods of fuzzy modeling for it because there are many cross-actions of technological variables, which could be seen while the burning process is in work. The methods that were listed and described in the Introduction of this article are very interesting and there was made reviewing about how it could be used for making modeling more quickly. However, most of them declare so many limitations for the technological parameters...
and their dynamics while kiln operating that they could not be engaged in the real control system because the real-time model should be the base of it.

In the next part of the article we will show some of methods that were used while modeling the cement kiln behavior. Figure 11 shows the control structure where is integrated the model of concentrations, loading on the main drive and additional variable that is the production of classical fuzzy method application. Here is the model of cement kiln and the control actions, which were made by a fuzzy control device (FCD), divided into four subdevices.

Input variables for the control object:
- Gaz – level of fuel supply to the burner, %;
- Air – the level of air supply to the kiln, defined as the percentage of opening the aspiration fan valve, %;
- V – speed of the kiln rotation (in the form of number of the gear ratio in the gearbox of the main engine);
Output variables for the control object:

- **Load** – load on the main kiln drive, %.
- **CO₂** – volume fraction of carbon dioxide in the exhaust gases, measured in the dust chamber, %;
- **CO** – volume fraction of carbon monoxide in the exhaust gases, measured in the dust chamber, %;
- **O₂** – volume fraction of oxygen in the exhaust gases, measured in the dust chamber, %;
- **Qsl** – consumption of sludge supplied for burning in the kiln, m³/h.

---

**Figure 10.** The results of the automated control system operation.

**Figure 11.** The fuzzy control structure with usage of classical fuzzy model.
If we will use the straight model of the control object without additional parameter which functionally connects the CO and O2 concentration components we will have $N = m^k = 5^4 = 625$ rules, where $m$ is the number of membership functions for each input variable and $k$ is the number of input variables.

In order to reduce the rule base we enter the additional control object part – the ACO with a new output variable – the intensity of gas burning in the kiln ($\text{Inten}$), in conditional fraction of a unit, corresponding to the power of the generated heat by the burned gas as functions of CO and O2 concentrations.

Taking into account the new factor, the kiln control device was divided into several components – fuzzy control devices (FCD). The first fuzzy control device (FCD1) controls the gas and air supply to the kiln depending on the fuzzy rule base for CO and O2; the second – FCD2 controls the speed of the kiln according to the fuzzy rule base for CO2 and a new factor – the intensity of gas burning ($\text{Inten}$); the third – FCD3 adjusts the kiln rotational speed depending on the main drive load ($\text{Load}$); the fourth – FCD4 controls the sludge supply to the kiln according to the fuzzy rule base of CO2 and the main drive load ($\text{Load}$). Thus, we represent the control of the kiln in the form shown in Figure 11.

Although the $\text{Inten}$ variable is the output for an additional control object, its calculation is performed by FCD1. As a result, the general rule base will be $N = 5^2 + 5^2 + 5^2 + 5^2 = 100$ rules. The final size of the rule base for this part of the kiln was reduced by 6.25 times.

The sample time for data selection is one minute. There was used the moving average filter for the input parameters (last 30 entries). The moving average filter was used due to some noise of the signal and is designed to smooth out jumps that do not carry an informative load caused by external influences. The sample time for the moving average is selected so that smoothing does not distort the actual behavior of the object.

For testing this control structure and model of the kiln there was written the software with fuzzy evaluations of current input variables. Figure 12 shows the main window of working model.

This version of the model can evaluate the kiln dynamics but the correlation is not upper than 67%, moreover, the reduced number model has about 2800 fuzzy rules without additional fuzzy rules that should be implemented by opinions of experts and technologist of the factory. The historical trends are shown in Figure 13. Therefore, to complete the
model of the kiln by classical method we would have spent about two years and any other kiln would make us remade about 30% of the rules. According to these results, we should have more common modeling method for constructing the cement kiln model.

The next version of model is the neuro-fuzzy model. The length of the kiln can be divided into 6 operational zones, characterized by various processes occurring in them: I – drying (evaporation); II – heating; III - decarbonization; IV – exothermic reactions; V – sintering; VI - cooling. The most important for control are zones I, II, III, and V. According to this method we should create four state estimation blocks for each of the kiln zones, the outputs of which will be fuzzy variables (Figure 14).

The drying zone state evaluation is carried out by the temperature of the exhaust gases ($T_{eg}$), vacuum after the kiln edge ($P_{ke}$) and additionally by the material temperature in the heating zone ($T_h$). The model of the drying zone estimation block (EBDZ) is presented in Figure 14a. The $Z_{dr}$ parameter reflects whether enough heat enters the drying zone, as well as the gas-dynamic kiln resistance, depending on the amount of viscous sludge hanging on the heat exchanger chains.

Estimation of the heating zone is carried out according to the material temperature in the heating zone ($T_h$). The $Z_h$ parameter estimates the temperature deviation from the norm. The model of the heating zone estimation block (EBHZ) is presented in Figure 14b.

The decarbonization zone is estimated by the vacuum in the kiln head ($P_{kh}$), the concentrations of carbon dioxide ($CO_2$) and oxygen ($O_2$) in the exhaust gases. The model of the decarbonization estimation block (EBDcZ) is presented in Figure 14c. The $Z_{dc}$ parameter shows how “weak” the kiln is, the decarbonization zone, from which subsequently unprepared material passes into the sintering zone.

The sintering zone is estimated by the load on the main kiln drive (Load), because overheating of the material in the sintering zone leads to increase in the lifting height of the material in the kiln and, consequently, to increasing the load moment. The model of the block for estimating the sintering zone (EBSZ) is presented in Figure 14d.

In addition to the blocks for state estimation of the kiln zones, there is another block introduced – the estimation block for evaluating the fuel combustion (EBFC) (Figure 14e), which is based on the concentration of carbon monoxide (CO) and oxygen (O2) in the exhaust gases, shows how much fuel is burned. The industrial regulations require that the CO component couldn’t be in exhaust gases.

Thus, we obtain five estimations of the kiln condition by its zones, on the basis of which the kiln could be controlled. It is worth noting that the blocks for estimation the sintering and heating zones are formally redundant. However, their inclusion in the control scheme allows more clearly show the control structure in accordance with the kiln division into zones and leaves it possible to enter additional parameters which may be the base of zone estimation. The whole kiln control circuit is shown in Figure 15.

The used additional variables are: Air gate – the percentage of open the air gate; $Q_{gas}$ – the fuel supply level to the burner, %; $V$ – the kiln rotation speed (in the form of number of the gear ratio in the main engine gearbox); $Q_{sl}$ – consumption of sludge supplied for burning in the kiln, m³/h; $T_{sa}$ – the secondary air temperature.
The fuzzy control device generates control actions depending on the kiln zones state. The feedback on control actions was entered because for a number of situations there are several control options possible and the choice of a particular one depends on the previous state of control actions.

It is necessary to select the corresponding membership functions (MF) to achieve good quantitative indicators from the control system for each specific object. The task of selecting membership functions is to find the parameters for the function of the selected type. In our case, we took the Gauss membership function \( f(x) = e^{-\frac{(x-\mu)^2}{2\sigma^2}} \). Here should be used the neural networks to find the parameters \( \gamma \) and \( \nu \).

Each linguistic variable can take three values: Z is zero (low); PS is a positive medium (normal); PB is a positive big (high).

Initially, the phase transitions will have random parameters \( \gamma \) and \( \nu \) (Figure 16). Then, during the operation of the network, these parameters will be adopted.

The neural network, which is equivalent to the described above fuzzy system, is shown in Figure 17.

The inputs of the neural network are linguistic variables; the output is a determined value of the technological value, for example, sludge flow rate. Hidden layers are rule layers.

The output values in the nodes of the first layer reflect the degree of correspondence to the input values to the linguistic variables associated with these nodes. The elements of the second layer calculate the values of the activation levels of the corresponding fuzzy rules. The output values of the neurons of the third layer correspond to the normalized values of

![Figure 14. Models of state estimations blocks.](image)

![Figure 15. Fuzzy control scheme for rotating kiln.](image)
these activation levels $c_i = a_i / \sum_{k=1}^{Q} a_k$. The output values of the fourth layer neurons are calculated as the multiplication result of the normalized values of the rules activation levels and values of the sludge consumption corresponding to their given (non-normalized) activation $c_i z_i$. The output neuron of the fifth layer summarizes the effects of the previous layer neurons.

Since the rotary kiln control circuit contains variables that characterize the kiln state but do not have physical analogues and correspondingly specific numerical values then the parameters adaptation of membership functions should be done by training a common neural network not separated into blocks. The view of the complete neural network is shown in Figure 18.

Membership functions are rigidly defined for intermediate variables characterizing the kiln state; they have the form shown in Figure 16, and could not be changed during the neural network training. Since these variables do not have similar physical parameters, their numerical values at the input of the neural network are taken from the previous training cycle of this network, which enters a delay in training by one cycle. However, with a sufficiently large number of clock cycles, this delay does not affect the training of the network.

It is possible to significantly reduce the total number of control rules and the probability of mutually exclusive rules of the occurrence by dividing the estimations by kiln zones according to the presented control scheme. At the same time, due to the control by evaluating all zones with one device, there is taken into account the interconnection of processes occurring along the entire length of the kiln.

Adaptation of membership functions using a neural network allows transferring the created fuzzy control system from one kiln to another, and
which has other operating features, without significant costs for the completion of the system.

Such a version of the control system is more convenient to the object because of learning implementation and it could be the base of the hierarchy structure of complex control system, but there are some questions about the time for learning the rules, the complexity of finding interconnections between kiln blocks.

So based on the above results it could be concluded that the proposed approach is less complex because the structure of nodes are coming from object working rules and the dynamics of each node is presented by the approximated curve of a real process which is suitable for technological variable and is shown by the order of fuzzy behavior chart. However, such a model consists of an adequate number of rules because the nodes could be linked according to the logic of process and so the rules reducing is more natural. Rules that are used in the proposed approach could be built based on the neuro fuzzy theory and according to the operating rules of the object. The additional advantage of such a method is using the technological conditions, which are described by process physics and complete the fuzzy rules of nodes by adding the potentially critical points of technological variables values or working state of working bodies.

3. Evaluation of fuzzy behavior chart results

One of the most important criteria for simulation result acceptance is the model adequacy. In the general case, adequacy is the degree of model conformity to a real phenomenon or an object, for the description of which it is developed. The model being created is focused on a specific subset of the object properties in accordance with the research objectives. The analysis of the model and the object adequacy is carried out for each output variable separately as the result of statistical samples comparison obtained by object and model corresponding output measuring [36, 37, 38].

The quality of kiln technological nodes operation was studied by the correlation analysis [39]. The developed program contains a special form that allows performing the necessary checks [40]. The results of the carried out experiments suggest that the obtained models satisfy the required level of adequacy and meet the requirements for accuracy since the strength of the correlation connection was noticeable and high. The following Figures 19, 20, 21, and 22 show some results of modeling.

The correlation of model and real operation is signed by $R_{xy}$ and the most important nodes of rotary kiln satisfy the required level of adequacy and meet the requirements for accuracy since the strength of the correlation connection was noticeable and high.

4. Pilot industrial tests of the automated control system

Figure 23 shows the structure of technical units complex for the automated process control system of the rotary kiln #1.

The complex of technical means of automation consist of:

1. Automated workstation (AWS) of the rotary kiln operator, which includes two workstations (duplicate each other) in the industrial version. The workstation communicates via Ethernet with the factory database and through Profinet network with the PLC S7-400. The automated workplace is located in the control room of machinists of rotary kilns.

2. A programmable logic controller (PLC) Siemens S7-400, which is a master of the Profinet network and consists of a central processor unit (CPU) and an interface module, which are located behind the control panels of the rotary kilns control room. It coordinates the overall control system.

3. PLC ET200S-1 with a number of I/O modules that is located in the gas treatment room and regulates the kiln gas supply.

4. PLC ET200S-2 with a number of I/O modules that is located near the main drive and controls kiln tilt angle to the horizon by regulating the hydraulic system of rollers.

5. PLC ET200S-3 with a number of I/O modules that is located near the kiln sludge feeder and controls the system feed by measuring the volume of sludge inlet.

6. PLC ET200S-4 with a number of I/O modules that is located in the main control cabinet and regulates the aspiration system and exhaust gas outlet treatment.

7. PLC ET200S-5 with a number of I/O modules that is located in the main control cabinet and controls its operation.

The automated process control system is built according to the principle of multi-level distributed control and the block principle, which ensures the possibility of the joint operation of units with remote control.
Figure 19. Results of modeling and real operation of node current load on the main drive.

Figure 20. Results of modeling and real operation of node oxygen concentration in the exhaust gas.

Figure 21. Results of modeling and real operation of node temperature of aspiration air.
of each, as well as the possibility of quick recovery of technical units when they fail.

This process control system is a two-level control system:

- the lower level – local control loops of the technological process, carried out by hardware and software of the PLC;
- the upper level is the control of the process, carried out and controlled from the automated workplace of operator made with SCADA-system Siemens WinCC.

The upper level includes the AWS control and visualization: 2 compatible computers with a monitor (Figure 24), which provide:

- display of technological variables and parameters of the object;
- registration of values of technological variables and parameters;
- registration of operating staff actions;
- the output of control commands to the PLC;
- formation of system operating protocols;
- generating reports about the rotary kiln operation;
- transfer the information to the factory database.

Information from the sensors installed in the kiln unit enters a single database. The state of the burning process is a prerequisite for the stable operation of the rotary kiln. The received data is sent to the supervisory remote control system, with the help of which the system entering signals are processed (Figure 25). Since we modify the control system by adding the advising output, the operator has the online advices, embedded in the SCADA-system.

One of the main problems that lead to the performance decrease of a rotary kiln is its transfer by operator or machinist to a slow or medium speed. According to the technical information about the burning process, the quantity of such transfers in terms of hours makes from 55 to 75 h per month. One hour of inactivity causes performance reduction by 10 tons of clinker. Implementing the control system usage at a cement plant as the experts evaluate will lead to the reduction of transfers into slow and medium speed and as well the kiln abnormal operation time to 5–10 h,
which will allow increasing the number of products by 9000 tons per year.

5. Summary

This work proposes an original method of dynamic process modeling based on the fuzzy behavior charts of the second rank, formally reflecting the interaction of rotary kiln technological nodes taking into account their mutual influence and the operating of kiln unit for the production of cement clinker as a whole. A distinctive feature of the developed model is the ability to cover a greater amount of information about the burning process, as well as to provide a higher level of change detail in comparison with existing counterparts through the use of fuzzy behavior charts of the second rank, which allow to take into account not only the fact of changing the technological variable behavior but also to determine the trend of this changing by taking into account information about the signs of the first and second derivatives.

When working with the alternative methods considered in the introduction, it was revealed that the creation of a cement kiln model on their basis requires serious limitations when reviewing the technological parameters of the object and for the further functionality of the automated control system. Therefore, the construction of such a model will not provide the required flexibility and quality for the advising control of the process.

The constructed model is a basis of the developed advising control system with intelligent properties, providing the operator with the...
necessary data to maintain the clinker burning process, significantly expanding the possibilities for revealing abnormal and emergency situations.

6. Conclusion

The experiments carried out form a basis for suggesting that the developed software application satisfies the required level of the mathematical model adequacy to the real burning unit and meets the accuracy requirements. The use of an automated control system that operates on the basis of obtained models and algorithms increases the efficiency of clinker burning complex technological processes, provides an opportunity to identify a wider range of abnormal and emergency situations, ensuring the increase of finished product output.

Thus, because of the described research, it is possible to talk about the possibility of application the control system development method based on fuzzy behavior charts of node of the second rank also for automation other complex technological objects, when nonstationarity, a large number of external and internal disturbances do not allow the research and modeling using classical mathematical techniques and control theory methods.

Declarations

Author contribution statement

Alexander Bazhanov: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Roman Vashchenko: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Vasily Rubanov: Contributed reagents, materials, analysis tools or data; Wrote the paper.

Funding statement

Research is carried out with the financial support of The Ministry of Science and Higher Education of the Russian Federation within the Public contract project #2.1396.2017/4.6.

Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

References

[1] Yu.V. Sharikov, F.Yu. Sharikov, O.V. Titov, Optimal control of annealing during the preparation of aluminum hydrate and cement clinker in tubular rotary kilns, Theor. Foundat. Chem. Technol. 51 (4) (2017) 503–507.
[2] V.A. Kuznetsov, A.V. Trulev, Computing simulation of natural gas combustion in a cement rotating kiln, Mod. Sci. Res. Ideas Res. Technol. 2 (10) (2012) 108–112.
[3] A.V. Bekarevich, V.G. Salikhov, B.T. Gaisimov, M.V. Shabin, Practical aspects of the automated detection and elimination of cracks in the coating and lining of a rotary kiln without its stoppage, Metallurgist 54 (7–8) (2010) 479–484.
[4] M.Z. Salikhov, Z.G. Salikhov, Intelligent system for automatic control of powerful rotating kilns, designed for sintering of free-flowing metallurgical materials using associative knowledge bases, Tsvetnye Met. 7 (2017) 90–96.
[5] Yu.V. Sharikov, F.I. Sharikov, Control systems using mathematical models of technological objects in the control loop, Math Des. 1 (2016) 4–8.
[6] M.V. Nuan, P.A. Traubev, V.K. Klages, Advisory system for a cement rotary kiln management with wet production method, Basic Res. (10) (2013) 1699–1703.
[7] C. Csernyel, A.G. Stratanam, Numerical modeling of a rotary cement kiln with improvements to shell cooling, Int. J. Heat Mass Tran. 102 (2016) 610–621.
[8] L. Qian, Y. Zhang, X. Su, Cement rotary kiln control system realized by PROFIBUS based on multi-agent, in: Proceedings – 2011 8th International Conference on Fuzzy Systems and Knowledge Discovery, FSKD, 2011, pp. 1364–1367.
[9] S.M. Zanoli, C. Pepe, M. Rocchi, Cement rotary kiln control system handling and optimization via model predictive control techniques, in: Australian Control Conference, 2015, pp. 288–293.
[10] S.M. Zanoli, C. Pepe, M. Rocchi, Control and optimization of a cement rotary kiln: a model predictive control approach, in: Indian Control Conference ICC, 2016, pp. 111–116.
[11] T. Hanein, F.P. Glasser, M.N. Bannerman, One-dimensional steady-state thermal model for rotary kilns used in the manufacture of cement, Adv. Appl. Ceram. 116 (4) (2017) 207–215.
[12] K.S. Mujumdar, A. Anza, V.V. Ranade, Modeling of rotary cement kilns: applications to reduction in energy consumption, Ind. Eng. Chem. Res. (2006) 2315–2330.
[13] K.S. Mujumdar and V.V. Ranade Rotary Cement Kilns Simulator (RCKS): integrated modeling of pre-heater, calciner, kiln and clinker cooler. Chem. Eng. Sci. 62(9), pp. 2950 – 2967.
[14] D.C.Q. Rodrigues, A.P. Soares Jr., E.F. Costa Jr., A.O.S. Costa, Mathematical modeling of a rotary kiln employed in the clinker production, Ceramics (2013) 302–309.
[15] D.C.Q. Rodrigues, A.P. Soares, E.F. Costa Jr., A.O. Costa Jr., Mathematical modeling of the temperature profiles of gas, solid, and kiln’s wall, and the concentration profiles of the main chemical species present inside the rotary kiln used in clinker production, Ceramica 56 (362) (2016) 140–146.
[16] S. Russ-Anghel, On mathematical modeling and unconventional control of clinker kiln in cement plants, in: IOP Conference Series: Materials Science and Engineering, 2017.
[17] F. Bendis-Marand, L. Signac, T. Pointet, J.C. Trigeas, Identiﬁcation of nonlinear fractional systems using continuous time neural networks, in: IFAC Workshop on Fractional Differentiation and its Applications, 2006, pp. 402–407.
[18] E. Colina, M. Falconi, V. Moricho, J. Medina, A. Mora, Design of a supervisory control system for a clinker kiln operation, in: Proceedings - 2015 Asia-Pacific Conference on Computer-Aided System Engineering, 2015, pp. 387–391.
[19] O. Kadri, L.H. Mouss, Identiﬁcation and detection of the process fault in a cement rotary kiln by extreme learning machine and ant colony optimization, Acad. J. Math. Eng. 15 (2) (2017) 43–50.
[20] A.K. Pani, H.K. Mohanta, Online monitoring of cement clinker quality using multivariate statistics and Takagi-Sugeno fuzzy-inference technique, Contr. Eng. Pract. 57 (2016) 1–17.
[21] J.H. Zhao, T.Y. Chai, Intelligence-based temperature switching control for cement raw meal calcination process, IEEE Trans. Contr. Syst. Technol. 23 (2) (2015) 644–661.
[22] M.G. Sharabiany, A. Fatemi, B.N. Arabi, An adaptive neuro-fuzzy controller for cement kiln, in: Proceedings of 2011 2nd International Conference on Instrumentation Control and Automation, 2011, pp. 65–70.
[23] A. Sharifi, M.A. Shoorehdehi, M. Teshnehlab, Design of a prediction model for cement rotary kiln using wavelet projection fuzzy inference system, Cybern. Syst. (2012) 369–397.
[24] X.H. Shi, Q.J. Meng, X.M. Li, Z. Zheng, Y.X. Ma, Q.L. Ma, Matlab simulation of system with fuzzy control in kiln temperature, Appl. Mech. Mater. (2014) 680–683.
[25] Z.L. Li, W. Li, Application of fuzzy neural network controller for cement rotary kiln control system, Adv. Mater. Res. (2012) 531–535.
[26] S. Li, R. Li, W. Liu, The application of expert system and fuzzy control system in cement grate cooler system, in: Proceedings of the IEEE International Conference on Software Engineering and Service Sciences, ICSESS, 2017, pp. 770–773.
[27] J. Liu, Y. Zhu, P. Sun, Sintering status recognition system for cement rotary kiln, in: ICCASM 2010 – International Conference on Computer Application and System Modeling, Proceedings, 2010, pp. 13212–13216.
[28] P. Zhou, M. Yuan, Intelligent dynamic modeling for online estimation of burning zone temperature in cement rotary kiln, in: Proceedings of the World Congress on Intelligent Control and Automation (WCICA), 2015, pp. 6167–6171.
[29] H. Zermane, M. Mousse, Internet and fuzzy based control system for rotary kiln in cement manufacturing plant, Int. J. Comput. Intel. Syst. 10 (1) (2017) 825–850.
[30] S. Wang, F. Dong, D. Yuan, The design and implementation of a cement kiln expert system, in: Proceedings of the IEEE International Conference on Automation and Logistics, 2007, pp. 2716–2719.
[31] V.Z. Magergut, A.G. Bazhanov, P.P. Gaevoy, A.S. Kopylov, A.S. Kyzhuk, M.N. Serydyuk, A.V. Shiyam, About New Approaches to the Study of Rotating Clinker Kilns as a Control Object. Special Issue of 'Cement. Lime. Gypsum' Magazine 4, 2009, pp. 118–122 (special issue of reports from the 11th International Congress of Cement Manufacturing Companies 2009).
[32] V.Z. Magergut, V.A. Ignatenko, A.G. Bazhanov, The development of discrete models of continuous technological processes and the analysis of their application. Mathematical methods in engineering and technology - MMET-25 (text), in: The Collection of Works of the XXVth International Scientific Conference: in 10 Volumes. V. 8. Section 12. - Volgograd: VSTU, KHIPI, Kharkiv, 2012, pp. 87–88.
[33] A.G. Bazhanov, V.Z. Magergut, R.A. Vashchenko, Operation model of the cement kiln node “Material temperature in the drying zone” as a fuzzy behavior chart, in: Proceedings of the Int. Conf. On Information and Digital Technologies, IEEE Xplore. – Zilina, Slovakia, 2015, pp. 35–38.
[34] R.A. Vashchenko, A.G. Bazhanov, V.Z. Magergut, A.A. Stepnovy, Application of the model based on fuzzy behavior charts in the advising control system of rotary
Cement kiln, in: Information and Digital Technologies (IDT) 2016 Int. Conf. on. – Rzeszow, Poland, 2016, pp. 299–304.

[35] R.A. Vashchenko, A.G. Bazhanov, V.G. Rubanov. Systems analysis and formalization of interactions between technological variables of weakly formalized control object, Sci. J. Belgorod State Univ. Belgorod 2 (41) (2017) 122–128.

[36] V.E. Gmurman. Probability Theory of and Mathematical Statistics, ninth ed., Higher. sch., Ster., Moscow, 2003, p. 479.

[37] I. Gaidyshev. Analysis and Data Processing, SPb, 2001, p. 752.

[38] K.K. Vasiliev, M.N. Slezhyvy. Mathematical Modeling of Communication Systems, Ulyanovsk, USTU, 2008, p. 170.

[39] S.P.S.S. Tutorials. Pearson Correlation [Electronic Source], 2017. Access mode: http://libguides.library.kent.edu/SPSS/PearsonCorr.

[40] T. Kowalczyk, E. Pleszczyńska, F. Ruland. Grade Models and Methods for Data Analysis with Applications for the Analysis of Data Populations, Studies in Fuzziness and Soft Computing, 151, Springer Verlag, Berlin Heidelberg New York, 2004.