Fuzzy situational control of technological safety of petrochemical installations and complexes

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Abstract. The article deals with the issues of fuzzy modeling and situational analysis of the technological safety of petrochemical complexes and decision-making on their control under conditions of uncertainty and fuzzy initial information based on fuzzy set theory and fuzzy logic. A formal model for describing fuzzy situations is proposed in the form of a fuzzy set and a rational decision in various emergencies based on the criterion of the degree of fuzzy inclusion and the degree of fuzzy equality is made using the method of situational logic inference. One of the main directions of the organization of industrial production is to ensure the safety of technological processes (TP), which is largely determined by compliance with safety requirements, timely determination of the states and diagnostics of technological equipment and units, and the effectiveness of their control in various situations that arise in the technological cycle.

Keywords: fuzzy logic, fuzzy model, situational analysis, petrochemical complexes, technological safety.

One of the main directions of the organization of industrial production is to ensure the safety of technological processes (TP), which is largely determined by compliance with safety requirements, timely determination of the states and diagnostics of technological equipment and units, and the effectiveness of their control in various situations that arise in the technological cycle.

Statement of the problem.

Consider the technological process, given in general form as $TIP = (M^{TO}, R^M, S)$, where:

$M^{TO} = \{M_1^{TO}, M_2^{TO}, \ldots, M_n^{TO}\}$ is the set of models of technological equipment and units (of the technological system); $R^M$ is the set of connections between objects; $S$ is the set of states of objects.

The functioning of any TP can be considered as a sequence of state changes $S_t \in S = \{S_1, S_2, \ldots, S_n\}$ over a certain time...
interval \([t_0, t_k]\). The state \(S_i\) of the TP at each time point \(t^* \in [t_0, t_k]\) is characterized by a set of parameters \(Y_i = \{Y_i^{TT}, Y_i^{TO}, Y_i^{CV}\}\), where \(Y_i^{TT}\), \(i = 1,1\) are the parameters of the state of the technology of this process; \(Y_i^{TO}\), \(i = 1,1\) are the parameters of the state of equipment; \(Y_i^{CV}\), \(l = 1,1,\) are the parameters of the state of the control system.

TP can be subject to restrictions on normal operation \(\Psi \{Y_i^{TT}, Y_i^{TO}, Y_i^{CV}\} \leq 0\), depending on the set of parameters \(\{Y_i^{TT}, Y_i^{TO}, Y_i^{CV}\}\). Going beyond these restrictions means the transition of the TP into an emergency. These restrictions divide the space of all states of the TP into two sets: \(S^{OC}\) - a set of hazardous states and \(S^{PC}\) - a set of safe (workable) states, i.e. \(S = S^{OC} \cup S^{PC}\), \(S^{OC} \cap S^{PC} = \emptyset\). In turn, the set of hazardous states can be divided into two non-overlapping subsets \(S^{OC} = S^{OC1} \cup S^{OC2}\), \(S^{OC1} \cap S^{OC2} = \emptyset\), where \(S^{OC1}\) are the subsets of hazardous states of the TP in the zone of warning and maximum permissible values of technological parameters, \(S^{OC2}\) are the subsets of hazardous states of the TP in the zone of critical values of technological parameters. In the set of safe states, the area or point in which the operation of the TP is the safest is of greatest interest - the area of the technological safety center \(S_0 \in S^{PC}\).

If the technological process is characterized by critical parameters, all values of which lie in the zone of allowable values of \(S_0\), the current hazard can be considered zero hazard. If one or more parameters go into the zone of critical values of \(S^{OC1}\), the current hazard increases as the parameters approach the zone of critical values \(S^{OC2}\). It is intuitively clear that the current hazard of the process should depend on the set of critical parameters that are simultaneously in zone \(S^{OC1}\), on the degree of approach of each parameter to zone \(S^{OC2}\), and on the degree of influence of each critical parameter on the possibility of an emergency.

Suppose that each set of parameters \(y_i \in Y\), \(Y = (y_1, y_2, \ldots, y_p)\), the values of which describe the state of the object, corresponds to linguistic variables \(<y_1, T_i, D_i>\), where \(T_i = \{T_i^1, T_i^2, \ldots, T_i^m\}\) is the term-set of linguistic variables (LV), \(y_i\) is the set of linguistic values of a feature, \(m_i\) is the number of feature values; \(D_i\) is the base set of feature \(y_i\). Fuzzy variables \(<T_i^j, D_i, \tilde{C}_j>\) are used to describe the terms \(T_i^j (i \in L = \{1,2,\ldots,m_i\})\) corresponding to the values of feature \(y_i\), i.e., the value of \(T_i\) is described by fuzzy set \(\tilde{C}_j\) in the base set \(D_i\): \(\tilde{C}_j = \{<\mu_c(d) / d >, d \in D_i\}\).

Then the fuzzy situations that arise in the course of the system operation can be represented as a fuzzy set of the second level: \(\tilde{S} = \{<\mu_s(y_i) / (y_i) >, y_i \in Y\}\).

In this case, the task of assessing technological safety and making a rational decision in various emergencies, in essence, can be formulated as the task of determining and classifying fuzzy situations \(S_i \in S =\{S_1, S_2, \ldots, S_n\}\) using the method of situational logic inference. Then by comparing the input fuzzy situation \(\tilde{S}_0\) with each fuzzy situation from a certain set of typical fuzzy situations \(\tilde{S} = \{\tilde{S}_1, \tilde{S}_2, \ldots, \tilde{S}_n\}\), it is possible to determine the optimal response alternative (a sequence of actions), which transfers the system from state \(S_0\) to \(S_{*}\), where the set of system parameters \(\{Y_i^{TT}, Y_i^{TO}, Y_i^{CV}\}\) characterizes the "center" of indicators of technological safety of the production process.

The concept of the problem solution.

Let \(Y\) be the set of states of some object and \(\mu_1, \mu_2, \ldots, \mu_k\) be the membership functions for fuzzy clusters \(F_1, F_2, \ldots, F_k\). Fuzzy clusters form a fuzzy covering of set \(Y\), if and only if: \(\mu_1(y) + \mu_2(y) + \ldots + \mu_k(y) \geq 1, \forall y \in Y\).

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The quality of fuzzy covering can be assessed using the following characteristic [4, 5]:

\[ J_{(\mu)} = \min \sum_{i=1}^{k} \sum_{x \in X} (\mu_i(y))^2 \| y - V_i \|^2, \]

where \( V_1, V_2, \ldots, V_k \) are the centers of the clusters, \( V \in L \) is the vector space with norm \( \| \cdot \| \) generated by the scalar product, \( J_{(\mu)} \) determines the mean square deviations of the states from \( Y \) with respect to centers \( V_1, V_2, \ldots, V_k \).

**Algorithm for clustering fuzzy situations.**

Step 1. The initial classification of states by clusters is performed based on the clustering algorithm, and \( \mu_i(y), i=1, k \), characterizes the proximity of state \( y \) to the center of the \( i \)-th cluster.

Step 2. Cluster centers are refined using the following formula:

\[ V_i = \frac{1}{\sum_{j=1}^{k} (\mu_j(y))^2} \sum_{j=1}^{k} \frac{1}{\| y - V_j \|^2} \sum_{x \in X} (\mu_j(y))^2, \]

\[ i=1, k, y \in Y \subseteq L \]

Step 3. New covering \( F_1, F_2, \ldots, F_k \) is built, described by \( (\mu_1, \mu_2, \ldots, \mu_k) \) in accordance with the following rule:

\[ \mu_i(y) = \frac{1}{\| y - V_i \|^2} \sum_{j=1}^{k} \frac{1}{\| y - V_j \|^2}. \]

Step 4. The deviations of the \( T \) value \( \mu = (\mu_1, \mu_2, \ldots, \mu_k) \) from \( \mu \) are calculated. If \( \delta \leq \varepsilon \) is a certain threshold, then the algorithm is completed; otherwise, the transition to step 2 is performed.

The size of the training sample required to build the covering of the state of space of the object by clusters is one of the uncertain parameters to be determined during the training process.

The fuzzy clustering algorithm does not determine whether state \( y \) belongs to cluster \( F \), but to what extent \( y \) belongs to \( F \).

Let, in the process of cluster analysis, a fuzzy coverage of the state of space of an object by fuzzy clusters \( F_1, F_2, \ldots, F_k \) be constructed, and the current state of object \( S_0 \) is fed to the input of the information system (IS). In the process of \( S_0 \) recognition, a set of values \( \mu_{01}, \mu_{02}, \ldots, \mu_{0k} \) is determined that characterizes the correspondence of state \( S_0 \) to each cluster \( F_i, i=1, k \). If the obtained values of \( \mu_{01} \) lead to the fulfillment of a relation of the form \( \mu_{01} + \mu_{02} + \ldots + \mu_{0k} \leq 1 \) or \( \max_{i} \mu_{0i} \leq T \), where \( i \) is the number of the cluster, \( T \) is some threshold, then a decision is made to create a new fuzzy cluster \( F_{k+1} \), the center of which is \( S_0 \).

**Situational logic inference.**

The tasks of situational choice in the general case can be considered as tasks of determining the current state of the control object \( S^* \) and comparing it with each fuzzy situation from a certain set of typical fuzzy situations \( S = \{ \tilde{S}_1, \tilde{S}_2, \ldots, \tilde{S}_Y \} \).

To do this, as a measure of proximity between the current fuzzy situation \( \tilde{S}^* \) and the situation \( \tilde{S}_0 \) corresponding to the technological safety center, we will use the following two criteria: the degree of fuzzy inclusion and the degree of fuzzy equality.

Let

\[ \tilde{S}_i = \{< \mu_{Si}(y)/ y >\}, \tilde{S}_j = \{< \mu_{Sj}(y)/ y >\}; \]

\( y \in Y \) are some situations. Then the degree of inclusion of situation \( \tilde{S}_i \) in situation \( \tilde{S}_j \) is determined by the following expression:

\[ v(\tilde{S}_i, \tilde{S}_j) = \& v(\mu_{Si}(y), \mu_{Sj}(y)), \]

where

\[ v(\mu_{Si}(y), \mu_{Sj}(y)) = \& (\mu_{Si}(T_i) \rightarrow \mu_{Sj}(T_j)) \]

\[ = \mu_{Sj}(T_j) = \max \{1 - \mu_{Si}(T_i), \mu_{Sj}(T_j)\}. \]

Here \( v(\mu_{Si}(y), \mu_{Sj}(y)) \) is the degree of inclusion of the fuzzy set \( \mu_{Si}(y) \) in the fuzzy set \( \mu_{Sj}(y) \).

It is believed that situation \( \tilde{S}_i \) is fuzzy included in situation \( \tilde{S}_j \), \( \tilde{S}_i \subseteq \tilde{S}_j \), if the degree of inclusion \( \tilde{S}_i \) in \( \tilde{S}_j \) is not less than a certain threshold of inclusion \( \alpha^{inc}_i \), determined by the control conditions, i.e. \( v(\tilde{S}_i, \tilde{S}_j) \geq \alpha^{inc}_i \).

The determination of the inclusion threshold

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The existence of two mutual inclusions of situations $\tilde{S}_i$ and $\tilde{S}_j$ means that at the threshold of inclusion $\alpha^\ast_{inc}$, situations $\tilde{S}_i$ and $\tilde{S}_j$ are approximately the same. Such similarity of situations is called fuzzy equality and the degree of fuzzy equality $\mu(\tilde{S}_i, \tilde{S}_j)$ of situations $\tilde{S}_i$ and $\tilde{S}_j$ is defined as:

$$\mu(\tilde{S}_i, \tilde{S}_j) = \land_{\gamma \in \gamma_1} \mu(\mu_{\tilde{S}_i}(y), (\mu_{\tilde{S}_j}(y))) ,$$

where

$$\mu(\mu_{\tilde{S}_i}(y), (\mu_{\tilde{S}_j}(y))) = \land_{\mu_{\tilde{S}_i}(Y_i)} ((\mu_{\tilde{S}_j}(Y_i) \rightarrow \mu_{\tilde{S}_j}(Y_i)))$$

It is considered that situations $\tilde{S}_i$ and $\tilde{S}_j$ are fuzzy equal, $\tilde{S}_i \approx \tilde{S}_j$, if $\mu(\tilde{S}_i, \tilde{S}_j) \geq \alpha$, $\alpha \in [0; 1]$, where $\alpha$ is some threshold of fuzzy equality of situations.

If situations $\tilde{S}_i$ and $\tilde{S}_j$ are described by $p$ features, then for their $(p - q)$-generality, the fuzzy equality of $p - q$ features from set $Y$ [3] is sufficient.

If the features that describe the control object do not depend on each other, then from a certain situation $\tilde{S}_i$ we can go to any situation $\tilde{S}_j$ that has $(p - q)$-generality, with situation $\tilde{S}_i$, using no more than $q$ local (acting on the value of only one feature) controls. Then the degree of $(p - q)$-generality $k_{p-q}(\tilde{S}_i, \tilde{S}_j)$ of situations $\tilde{S}_i$ and $\tilde{S}_j$ is determined by the following expression:

$$k_{p-q}(\tilde{S}_i, \tilde{S}_j) = \land_{\gamma_{1, q}} \mu(\mu_{\tilde{S}_i}(y), (\mu_{\tilde{S}_j}(y))) ,$$

where $|\gamma_{1, q}| \leq q$, feature $y_k$ belongs to $Y_q$, if $\mu(\mu_{\tilde{S}_i}(y_k), (\mu_{\tilde{S}_j}(y_k)) < \alpha$, for $Y_q = \emptyset$ situations $\tilde{S}_i$ and $\tilde{S}_j$ are fuzzy equal.

Let the set of possible states of the control object be given by set $S$ of reference fuzzy situations. It is assumed that the set of reference situations $S$ is complete. Based on expert information, each fuzzy situation $\tilde{S}_i \in S$ is associated with control decision $r_i \in R$, where $R$ is the set of control decisions used to control the object. The fuzzy situational logic inference is reduced to recognizing an input fuzzy situation $\tilde{S}_0$ describing the current state of the control object, and issuing a control decision corresponding to it from set $R$. Two methods are proposed for recognizing a fuzzy situation: the “nearest neighbor” method in the space of reference fuzzy situations and issuing control decisions taking into account all reference situations.

As a measure of the similarity of fuzzy situations, the degree of fuzzy inclusion of fuzzy situations and the degree of fuzzy equality are most preferable. Both of these measures consist in calculating the degree of similarity in the interval $[0; 1]$. The highest degree of similarity is 1, the lowest is 0. The degree of similarity of 0.5 means complete uncertainty.

Thus, the use of the above methodology for formalizing the dynamics of the functioning of petrochemical complexes based on the theory of fuzzy sets and fuzzy logic makes it possible to develop a set of measures aimed at managing the technological safety of petrochemical facilities and, accordingly, at reducing losses and increasing the efficiency of maintenance personnel by improving the state of health and failure prediction of technology, equipment, and control systems.

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