Formalization of the task of monitoring the technological safety of industrial facilities in conditions of indistinctness of the initial information

I X Siddikov¹, N Yu Mamasodikova², M A Khalilov³, A K Amonov³ and G B Sherboboyeva⁴

¹Tashkent State Technical University, 2, Universitetskaya street, Tashkent, 100095, Uzbekistan
²Fergana branch of Tashkent University of Information Technologies named after Mukhammad al-Khwarizmi, 185, Mustaqillik street, Fergana, 150118, Uzbekistan
³Samarkand branch of Tashkent University of information technologies named after Mukhammad al-Khwarizmi, 47A, Sh. Mirzo Street, Samarkand, 140100, Uzbekistan
⁴Karshi branch of Tashkent University of information technologies named after Mukhammad al-Khwarizmi, 3, Beshkent Street, Karshi, 180100, Uzbekistan

E-mail: nodiramamasodikova@mail.ru

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 management in conditions of uncertainty and fuzzy initial information based on the theory of fuzzy sets and fuzzy logic. A formal model for describing fuzzy situations in the form of a fuzzy set and making rational decisions in various emergency situations based on the criterion of the degree of fuzzy inclusion and the degree of fuzzy equality with the involvement of the method of situational inference is proposed.

1. Introduction

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, as well as the efficiency of their control in various situations arising in the technological cycle.

An analysis of the principles of constructing systems for diagnostics and control of technological safety of petrochemical plants and complexes leads to the conclusion that an essential feature of this class of systems is the presence of a large number of input and output parameters that characterize the state of the system in an ambiguous way, lack or incompleteness of knowledge about the physicochemical parameters of the process. Additional difficulties in solving problems of diagnostics and management of technological safety by complex technical systems in various emergency situations arise due to the fact that decisions are generally made in conditions of uncertainty and indistinctness of the initial information and there is practically no possibility of using existing deterministic-stochastic models [1-3].
For effective management of such complex technological processes, it is necessary to develop new approaches, models and methods for assessing the states of technological equipment and processes, methods and algorithms for ensuring the safety of the operation of objects in various production and technological situations based on the use of modern information technologies and intelligent decision support tools [1, 2, 4].

The paper presents one of the possible approaches for situational analysis and assessment of the states of control objects, as well as methods of situational inference in conditions of uncertainty and fuzzy initial information.

2. Formulation of the problem

Let us consider the technological process, given in general as follows: \( TP = (M_{TO}^T, R^M, S) \) where:

\[ M_{TO}^T = \{M_1^{TO}, M_2^{TO}, \cdots, M_n^{TO}\} \] - many models of technological equipment and units (technological system); - a lot of connections between objects; \( S \) is a set of states of objects.

The function of any TP can be consider as a sequence of state changes \( S_i \in S = \{S_1, S_2, \cdots, S_n\} \) over a certain time interval \([t_0, t_k]\). The state \( S_i\) of TP at each moment of time \( t^* \in [t_0, t_k] \) is characterized by a set of parameters \( Y_i = \{Y_i^{TP}, Y_i^{TO}, Y_i^{CV}\} \), where: \( Y_i^{TP}, i = 1, I \) parameters of the state of the technology of this process; \( Y_i^{TO}, i = 1, J \) - equipment conditions parameters; \( Y_i^{CV}, 1 = 1, L \) - parameters of the state of the control system.

The TP may be subject to restrictions on normal operation \( \Psi \{Y_i^{TP}, Y_i^{TO}, Y_i^{CV}\} \leq 0 \) depending on the sets of parameters \( \{Y_i^{TP}, Y_i^{TO}, Y_i^{CV}\} \). Going beyond these restrictions means the transition of TP to an emergency situation. Thus, these restrictions divide the space of all states in which the TP can be located into two sets: \( S^{OC} \) - a set of dangerous states and \( S^{PC} \) a set of safe (operable) states, that is \( S = S^{OC} \cup S^{PC}, S^{OC} \cap S^{PC} = \emptyset \). In turn, the set of hazardous states can be divided into two non-intersecting subsets: \( S^{OC} = S^{OC_1} \cup S^{OC_2}, S^{OC_1} \cap S^{OC_2} = \emptyset \), where \( S^{OC_i} \) are subsets of hazardous conditions of TP in the zone of warning and maximum permissible values of technological parameters, \( S^{OC_2} \) - subsets of hazardous states of TP in the zone of critical values of technological parameters. In the set of safe states, the most interesting is the area or point where the operation of the TP is the safest - the area of the technological safety centre \( S_0 \in S^{PC} \).

If the technological process is characterized by hazardous parameters, all values of which are in the range of permissible values \( S_0 \), the current hazard can be considered zero. In the event that one or several parameters go into the zone of dangerous values \( S^{OC_i} \), the current hazard increases, and it will increase as the parameters approach the zone of critical values \( S^{OC_2} \). It is intuitively clear that the current hazard of the process should depend on a multitude of hazardous parameters simultaneously located in the zone \( S^{OC_i} \), on the degree of approach of each parameter to the zone and on the degree of influence of each hazardous parameter on the possibility of an emergency.

Suppose that each set of parameters \( y_i \in Y, Y = (y_1, y_2, \cdots, y_p) \), the values of which describe the state of the object, correspond to linguistic variables \( <y_i, T_i, D_i> \), where \( T_i = \{T_1^i, T_2^i, \cdots, T_m^i\} \) is a term-set of linguistic variables (LP), \( y_i \) is a set of linguistic values of a feature, \( m_i \) is the number of
values of a feature; \( D_i \) - the base set of the feature \( y_i \). Fuzzy variables \( < T'_j, D_i, \tilde{C}'_j > \) are used to describe the terms \( T'_j (i \in L = \{1,2,...,m_j\}) \) corresponding to the attribute values \( y_i \) that is \( T'_j \) - described by a fuzzy set \( \tilde{C}'_j \) in the base set \( D_i \):

\[
\tilde{C}'_j = \{ \mu_{C'_j}(d) / d \geq \}, \; d \in D_i \]

Then the fuzzy situation arising in the process of the system functioning can be represent as a fuzzy set of the second level:

\[
\tilde{S} = \{ \mu_{y_j}(y_j) / (y_j) > \}, \; y_j \in Y
\]

In this case, the task of assessing technological safety and making rational decisions in various emergency situations, in essence, can be formulated as the task of determining and classifying fuzzy situations \( S_i \in S = \{S_1, S_2, \cdots , S_n\} \) using the method of situational inference. Then, comparing the input fuzzy situation \( \tilde{S}_0 \) with each fuzzy situation from a certain set of typical fuzzy situations \( \tilde{S} = \{\tilde{S}_1, \tilde{S}_2, \cdots , \tilde{S}_Y\} \), it is possible to determine the optimal response alternative (sequence of actions), which transfers the system from state \( S'_0 \) to \( S_i \) state, where the set of system parameters \( \{Y^{TP}_i, Y^{TO}_i, Y^{CV}_i\} \) characterizes the "centre" of technological safety indicators of the production process.

The concept of solving the problem. Let be the \( Y \) - set of states of some object, \( \mu_1, \mu_2, \ldots, \mu_k \) is the membership function for fuzzy clusters \( F_1, F_2, \ldots, F_k \). Fuzzy clusters form a fuzzy cover of \( Y \) a set if and only if:

\[
\mu_1(y) + \mu_2(y) + \ldots + \mu_k(y) \geq 1, \forall y \in Y
\]

The quality of a fuzzy coverage can be assessed using the following characteristic [4.5]:

\[
J_{(\mu)} = \min \sum_{i=1}^{k} \sum_{y \in X} (\mu_i(y))^2 \|y - V_i\|^2, \; \text{where} \; V_1, V_2, \ldots, V_k \; \text{are the centres of the clusters}, \; V_i \in L \; \text{is the vector space with the norm} \| \|, \; \text{generated by the scalar product}, \; J_{(\mu)} \; \text{and determines the standard deviations of states from} \; Y \; \text{relative to the centres} \; V_1, V_2, \ldots, V_k.
\]

3. Algorithm for clustering fuzzy situations

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

Step 2. Cluster centres are specified using the formula:

\[
V_i = \frac{\sum_{y \in X} (\mu_i(y))^2 y}{\sum_{y \in X} (\mu_i(y))^2}, i = 1, k, y \in Y \subset L
\]

Step 3. A new pavement \( F_1, F_2, \ldots, F_k \) is built, described using \( \mu_1, \mu_2, \ldots, \mu_k \) in accordance with the rule:

\[
\mu_i(y) = \frac{1}{\|y - V_i\|^2} / \sum_{j=1}^{k} \frac{1}{\|y - V_j\|^2}
\]
Step 4. Deviations of $T$ value $\mu = (\mu_1, \mu_2, ..., \mu_k)$ from $\mu = (\mu_1, \mu_2, ..., \mu_k, \mu)$. If $\delta \leq \varepsilon$ is a certain threshold, then the algorithm is completed; otherwise, go to step 2.

The size of the training sample required to construct the coverage of the object state space by clusters is one of the undefined parameters that must be determined in the training process.

Using the fuzzy clustering algorithm, it is not determined whether a state $y$ belongs to a cluster $F$, but to what extent $y$ belongs to $F$.

Suppose that in the process of cluster analysis a fuzzy coverage of the object state space by fuzzy clusters $F_1, F_2, ..., F_k$ was built and the current state of the object $S_0$ is fed to the input of the information system (IS). In the process of $S_0$ recognition, a set of $\mu_{01}, \mu_{02}, ..., \mu_{0k}$ values is determined that characterizes the correspondence of the $S_0$ state to each cluster $F_i, i = 1, k$. If the obtained values of $\mu_0$ lead to the fulfillment of a relation of the form $\mu_{01} + \mu_{02} + ... + \mu_{0k} \leq T$ or maximally, $\mu_{0i} \leq T$ where $i$ is the cluster number, $T$ is a certain threshold, then a decision is made to create a new fuzzy cluster $F_{k+1}$, the centre of which is $S_0$.

Situational inference. In the general case, situational choice problems can be considered as problems of determining the current state of the control object $\tilde{S}_i$; and comparing it with each fuzzy situation from a certain set of typical fuzzy situations $S = \{\tilde{S}_1, \tilde{S}_2, ..., \tilde{S}_N\}$.

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

Let $\tilde{S}_i = \{< \mu_{Si}(y)/y >, \tilde{S}_j = \{< \mu_{Sj}(y)/y >, (y \in Y)$ there are some situations. Then the degree of inclusion of the situation $\tilde{S}_i$ in the situation $\tilde{S}_j$ is determined by the expression:

$$v(\tilde{S}_i, \tilde{S}_j) = \& \ v(\mu_{S_i}(y), \mu_{S_j}(y)),$$

where

$$v(\mu_{S_i}(y), \mu_{S_j}(y)) = \& \ (\mu_{\delta i}(T_i^l) \rightarrow \mu_{\delta j}(T_j^l)),$$

$$\mu_{\delta i}(T_i^l) \rightarrow \mu_{\delta j}(T_j^l) = \max\{1 - \mu_{\delta i}(T_i^l), \mu_{\delta j}(T_j^l)\}.$$

Here $v(\mu_{S_i}(y), \mu_{S_j}(y))$ is the degree of inclusion of a fuzzy set $\mu_{S_i}(y)$ in a fuzzy set $\mu_{S_j}(y)$.

It is considered that the situation $\tilde{S}_i$ is not clearly included in the situation $\tilde{S}_j$, i.e. $\tilde{S}_j, \tilde{S}_i \subseteq \tilde{S}_j$ if the degree of inclusion $\tilde{S}_i$ in $\tilde{S}_j$ is not less than a certain switching threshold $\alpha_{inc}^*$, determined by the control conditions, that is $v(\tilde{S}_i, \tilde{S}_j) \geq \alpha_{inc}^*$. The determination of the switch-on threshold point $\alpha_{inc}^*$ mainly depends on the properties of the control object and the requirements for the quality of control.

The existence of two mutual inclusions of situations $\tilde{S}_i$ and $\tilde{S}_j$ means that at the threshold $\alpha_{inc}^*$ of inclusion of 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 follows:

$$\mu(\tilde{S}_i, \tilde{S}_j) = \& \ \mu(\mu_{S_i}(y), (\mu_{S_j}(y))).$$
where
\[
\mu(\mu_{Si}(y), (\mu_{Sj}(y)) = \\&((\mu_{\mu_{di}}(T_i^j) \rightarrow \mu_{\mu_{dj}}(T_j^i))) \& (\mu_{\mu_{dj}}(T_j^i) \rightarrow \mu_{\mu_{di}}(T_i^j))).
\]

It is considered that situations \( \tilde{S}_i \) and \( \tilde{S}_j \) are fuzzy equal, \( \tilde{S}_i \sim \tilde{S}_j \), if \( \mu(\tilde{S}_i, \tilde{S}_j) \geq \alpha \), \( \alpha \in [0.6; 1] \), where 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, a rather fuzzy equality of \( p - q \) features from the set \( Y \) [3].

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

\[
k_{p-q}(\tilde{S}_i, \tilde{S}_j) = \&_{y \in Y_q} \mu(\mu_{Si}(y), (\mu_{Sj}(y))),
\]

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

Let the set of possible states of the control object be specified by a set \( S \) of reference fuzzy situations. It is assumed that the set of reference situations is complete. On the basis of expert information, each fuzzy situation \( \tilde{S}_i \in S \) is associated with a control decision \( r_i \in R \), where \( R \) is a set of control decisions used to control the object. Fuzzy situational logical inference is reduced to recognizing an input fuzzy situation \( \tilde{S}_0 \) describing the current state of the control object, and issuing the corresponding control solution from the set \( R \). To recognize a fuzzy situation, two methods can be proposed: the “nearest neighbour” method in the space of reference fuzzy situations and the issuance of control decisions taking into account all reference situations.

As a measure of the similarity of fuzzy situations, the most preferred are the degree of fuzzy inclusion of fuzzy situations and the degree of fuzzy equality. 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 0.5 means complete uncertainty.

4. Conclusion
Thus, the use of the above-described 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 operability and predicting failures of technology, equipment and control systems.

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