The study object: the chemical engineering system for production of benzene and optimization of the system operation modes based on modeling. An approach to the effective solution of problems of optimization of operating modes of real chemical engineering systems was proposed. Since such systems are usually multicriterial and characterized by the fuzziness of initial information, an approach to the development of their models and optimization of their operating modes in a fuzzy environment was proposed. The essence of this approach lies in the construction of mathematical models and optimization of system operation modes based on the system analysis methodology using available information of deterministic, statistical, and fuzzy nature. Statements of the problems of optimization by means of chemical engineering systems in a fuzzy environment have been obtained by modifying various principles of optimality for working in a fuzzy environment. Based on a modification of the principles of maximin and Pareto optimality, a heuristic algorithm for solving the formulated optimization problem was proposed based on the use of knowledge and experience of decision-makers. The proposed method of model construction and an optimization algorithm were implemented in practice when constructing models of benzene and rectification columns of a chemical engineering system of production of benzene when formulating and solving the problem of optimizing their operation modes in a fuzzy environment. Analysis and comparison of optimization results allow us to conclude about the effectiveness of the proposed fuzzy approach to solving optimization problems in a fuzzy environment. As a result of optimization of the benzene production process, the benzene yield increased by 1.45 thousand t or by 1.1 %, the raffinate output volume increased by 0.4 thousand t in conditions of upholding constraints on benzene quality. The proposed approach makes it possible to assess the degree of upholding of fuzzy constraints

Keywords: mathematical modeling, fuzzy information, chemical engineering system, optimality principles, heuristic algorithm

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METHODS OF CONSTRUCTING MODELS AND OPTIMIZING THE OPERATING MODES OF A CHEMICAL ENGINEERING SYSTEM FOR THE PRODUCTION OF BENZENE IN A FUZZY ENVIRONMENT

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1. Introduction

In practice, many complex chemical engineering systems (CES) are characterized by the fuzziness of initial information which complicates the process of developing models and optimizing their operating modes. The approach using expert methods [1–4] and methods of fuzzy sets [5–8] form the most effective approach to mathematical description, op-

timization, and control of operating modes that are complex in conditions of initial information in a fuzzy environment. The process objects of oil refining factories belong to complex chemical engineering systems in which technological processes of working up raw materials and production of petroleum products take place. They often function with fuzzy information. Therefore, it is necessary to take into account the criterion vectors and fuzziness of initial information for multicriteria optimization when controlling the operating modes of such systems.

As a rule, such problems are formalized as multicriteria problems solved on the basis of knowledge and experience of experts and decision-makers, i.e., heuristic approach. Thus, mathematical models of complex chemical engineering systems and methods of optimizing their operating modes are developed on the basis of fuzzy information in a form of experience and knowledge of a human operator and a decision-maker [9, 10].

The fuzzy approach has led to the emergence of methods for solving multicriteria optimization problems when controlling a system in a fuzzy environment, using the methodology of systems analysis, knowledge and experience of the decision-maker and his preferences when searching for solutions [11]. For the purpose of formalizing and applying the initial fuzzy information for the construction of mathematical models and control of CES, methods of expert assessments and the theory of fuzzy sets (TFS) can be successfully used. To successfully solve the problems of modeling and optimization when controlling the CES operating modes under fuzzy conditions, it is necessary to develop a method for constructing models based on available information of a diverse nature. It is also necessary to further develop methods for solving problems of multicriteria optimization when controlling the CES operating modes in a fuzzy environment which are urgent problems in chemical technology and oil refining.

2. Literature review and problem statement

The results of studies on the development of mathematical models of metallurgical technological complexes based on a hybrid approach including the use of fuzzy information were presented in [7]. This study has shown that in practice, it is necessary to use any various available information because of a lack of information on modeling and production management. However, the issues related to the gathering and formalization of fuzzy information have remained unresolved. This can be caused by difficulties, considerable financial and time costs required for organizing, conducting an expert assessment, and processing of the results. All this can lead to the inappropriateness of the corresponding study methods. The method of automated expert assessment and processing of results, creation of expert systems can be an option for overcoming the corresponding difficulties. It is this approach that was proposed in [4] but the creation of such systems can also be quite costly and economically inexpedient.

The problems of multicriteria optimization [10] and fuzzy optimization [12] were studied in [10, 12]. To optimize objects and processes in conditions of fuzziness of initial information, it was proposed to transform the original fuzzy problem into an equivalent system of clear problems. In doing this, such a transformation has to be carried out on the basis of the α level set of theories of fuzzy sets. However, such transformation of a fuzzy problem causes loss of sometimes important part of the original fuzzy problem and respectively, to a decrease in the adequacy of the solutions obtained. Therefore, there is a need to develop a fuzzy approach to solving the initial problem in a fuzzy environment. This approach was proposed in [13]. However, the proposed approach does not consider the issues of the practical application of the proposed algorithms and does not substantiate their performance and efficiency. Therefore, the issues of practical application and efficiency of fuzzy approaches remain important and urgent problems in the field of fuzzy modeling, optimization, and control of complex chemical engineering systems operating in a fuzzy environment.

The optimization issues arising in designing technological systems in the presence of numerous criteria and parameters were studied in [14]. This study proposed to solve the problems of uncertainty arising in designing complex systems based on average statistical data taking into account the opinions of designers (experts). However, the issues of accounting for ambiguity in the opinions of experts were not considered.

The results obtained in the study of maximizing the productivity of the technological process of decomposition [15] and hydrogen production [16] were presented. The issues of the practical application of optimization algorithms for production optimization were presented in detail. However, these studies did not take into account the issues of solving the multicriteria and fuzzy problems taking place in the processes occurring in complex CES.

A mathematical model used to solve the control problem was constructed in [17]. However, insufficient attention was paid to verification and substantiation of the developed model adequacy. This can lead to inefficiency of the control process. Questions and problems concerning the application of heuristic algorithms in data analysis to solve the problem of diagnosing the object state were studied in [18]. However, this study did not cover the problems of developing such heuristic algorithms and their application to control the modes of operation of complex chemical engineering systems.

The issues of mathematical modeling and risk assessment in object management using the fuzzy logic technique were studied, a complete rule base was built and the results of fuzzy modeling were presented in [19]. As a disadvantage, it can be noted that there is no comparison of the results obtained there with the results of other well-known research works, e.g. [20] on risk assessment in a fuzzy environment. However, only the problems of assessing the risk in the economy were considered in [20] and the problems of assessing technical and technological risks in CES optimization were not considered because of the fuzziness of the initial information.

All this allows us to assert that it is expedient to conduct a study dedicated to the effective expert assessment of formalization of fuzzy information, development, and practical application of a heuristic algorithm of solving the fuzzy optimization problem. It should also be noted that it is necessary to develop a fuzzy approach to solving a fuzzy problem without transforming it into a system of clear problems for the adequate solution of CES control problems in a fuzzy environment.

3. The aim and objectives of the study

The study objective implied developing methods of constructing models and optimizing CES operating modes in a

fuzzy environment using the example of a benzene production complex. This will make it possible to build adequate models of the benzene production process and find optimal operating modes of the complex that will maximize the benzene yield with specified quality indicators.

To achieve the objective, the following tasks were set:

– develop an algorithm of constructing CES models using available information of diverse nature;

– construct mathematical models of benzene production CES taking into account fuzziness of initial information;

– formulate a statement of a problem of optimization of control of the CES operation modes in a fuzzy environment;

– develop a heuristic algorithm of effective solution of the problem of the set multicriteria optimization problem in a fuzzy environment;

– implement the study results in optimizing operating modes of the CES of benzene production.

4. Materials and methods used in studying the CES of benzene production, methods of constructing models, and optimization in a fuzzy environment

As a study object, the CES of benzene production at the Atyrau Refinery (Republic of Kazakhstan) was considered for which it was necessary to determine optimal values of operating parameters. These optimal values of operating parameters should ensure effective control of operating modes according to the criteria vector under fuzzy constraints. This requires the development of mathematical models of main units of the CES, formulation of the statement of the optimization problem in controlling the CES under conditions of fuzziness of initial information, and development of an effective method for this problem solution.

The input and operating parameters of the CES of benzene production which affect the CES operating modes include the volume of raw materials, i.e. reformate (x_1), temperature (x_2), and pressure (x_3) in the benzene column (BC). Besides, the operation modes are also influenced by quality indicators of benzene: proportion of sulfur (x_4) and aromatic hydrocarbons (HC) in the feedstock (x_5). Output parameters of the object control, i.e., the control quality criteria include the yield (y_1) of the target product (benzene), volumes of raffinate (y_2), and heavy aromatics (y_3).

One of the difficulties of the problem being solved consisted in the need to control quality indicators of benzene determined by fuzzy constraints: "average octane number of benzenes is not less than..."; "sulfur content in benzene is not more than ...". To ensure the upholding of these fuzzy constraints, it is necessary to construct membership functions of upholding: $\mu_1(x)$; $\mu_2(x)$. The control process must be implemented in an interactive mode based on models and a heuristic algorithm taking into account the decision-maker preference. As a result of solving the problem of optimizing the operating modes of the CES of benzene production, it is necessary to determine the values of operating parameters (x_1, x_2, x_3, x_4, x_5) that provide the best values of the control criteria without violating the imposed constraints.

Let us concretize the main parameters of the multicriteria optimization problem when controlling the operating modes of a benzene production CES. The vector of control criteria is known: $f(x)=(f_1(x), f_2(x), f_3(x))$ where $f_1(x)$ is benzene yield, $f_2(x)$ is raffinate yield from the benzene column, $f_3(x)$ is the yield of heavy aromatics from the rectification column (RC). The minimum and maximum values of the considered criteria are known: $f_1(x)$=[127–138 thousand t]; $f_2(x)$=[77–86 thousand t]; $f_3(x)$=[445–456 thousand t] [21].

The vector of input and mode parameters $x=(x_1, x_2, x_3, x_4, x_5)$ affects the values of criteria $f_1(x)$, $f_2(x)$, $f_3(x)$ and fuzzy constraints $\varphi(x)$. The vector data can be measured with appropriate measuring instruments (x_1, x_2, x_3) or determined by laboratory analysis with human participation (x_4, x_5). Intervals of changing the operating parameters are known [22]. Based on the methods of expert assessments with the involvement of decision-makers for the CES of benzene production at the Atyrau refinery, it was necessary to construct membership functions (MF) of fulfilling fuzzy constraints $\varphi(x)=(\varphi_1(x), \varphi_2(x))$: $\mu_1(x)$ and $\mu_2(x)$, "the average octane number of benzene must be no less than 102" and "the sulfur content in benzene must be no more than 0.00005 %".

Experimental-statistical methods [23–25] and methods of the theory of fuzzy sets [6–9] were used to study the CES of benzene production in order to construct mathematical models of its main units. Statistical data were collected using the materials of regime sheets of the technological complex to produce benzene and the active experiments carried out at the object. The fuzzy information about the object and the benzene production process was collected on the basis of expert assessment methods, in particular, the Delphi method [4, 26]. Modified methods of sequential inclusion of regressors and the method of least squares were used [25–27] for structural and parametric identification of the models of the CES benzene column. Values of the regression coefficients were determined using the Regress software package (Russia). Formalization and statement of the problem of multicriteria optimization were carried out using the theory of optimization and fuzzy sets [5, 8, 10, 13, 14, 27]. To develop a heuristic method of solving the problem of multicriteria fuzzy optimization approaches to the development of heuristic methods were used [18, 28] in addition to the methods of optimization theory and fuzzy sets.

5. The results obtained in studying the models and optimization of operating modes of the benzene production complex

5. 1. Algorithm of constructing the models of a chemical engineering system using available information of various nature

To study, optimize and control the CES operating modes, it was necessary to develop mathematical models of the main system units describing the dependence of the system control criteria on its operating parameters. Based on the methodology of systems analysis, the following generalized algorithm of constructing CES models using the available information of diverse nature was proposed. It consists of the following main steps:

– Step 1. Study of the elements of the chemical engineering system, connections between the elements, collection, and processing of available information, establishing the modeling purpose.

– Step 2. Determination of the criteria of evaluating, comparing, and choosing the models that can be built for the CES elements taking into account the modeling purpose.

– Step 3. Conducting an expert assessment, i.e., ranking the types of models that can be built for each element of the chemical engineering system according to the selected crite-

ria and determining the optimal type of a model for each element of the system [9] based on the sum of the rank values.

– Step 3. 1. If the theoretical information to describe the operation of the CES element is sufficient and the construction of a deterministic model based on the sum of the values of the criteria is effective, then a deterministic model is built for this element. To build a deterministic model, analytical methods and theoretical information about the object and the process are used.

– Step 3. 2. If statistical data for describing the CES element operation are available and the statistical model gains the best value (the sum of the ranks), then statistical models of this element are built on the basis of experimental statistical methods. To construct a model, the method of sequential inclusion of regressors (to identify the model structure) and the least-squares method (to identify parameters. i.e. the regression coefficients) can be used here.

– Step 3. 3. If the theoretical and statistical data for describing the CES element are insufficient and the collection of such data is economically inexpedient, the fuzzy model gains the highest rank based on the sum of the rank estimates, then fuzzy models are constructed for it. To construct a fuzzy model, fuzzy information (experience, knowledge of experts in the subject matter) that describes the operation of this element must be available. In this case, the model is built on the basis of TFS methods in accordance with Step 4.

– Step 3. 4. If the theoretical, statistical, and fuzzy information about the object is insufficient and the construction of deterministic, statistical, and fuzzy models for the CES element is impossible or impractical, then a combined model is constructed for this element. When constructing a combined (hybrid) model, initial information of various types (theoretical, statistical, fuzzy) can be used by combining them. To do this, it is necessary to go to paragraphs 3.1–3.3 or Step 4 depending on the nature of the initial information

– Step 4. Fuzzy input, mode $\tilde{x}_i = \tilde{A}_i,\ \ i=\overline{1,n}$, and output (criteria) $\tilde{y}_j = \tilde{B}_j,\ \ j=\overline{1,m}$ parameters are determined where $\tilde{A}_i \in X,\ \tilde{B}_j \in Y$ are fuzzy subsets belonging to universal sets *X, Y*. Moreover, the parameters $x_i \in X_i,\ \ i=\overline{1,n}$ can be clear.

– Step 5. If the input parameters of the object are clear, i.e., $x_i \in X_i,\ \ i=\overline{1,n},$ then structures of fuzzy multiple regression equations $\tilde{y}_j = f_j\left(x_1,...,x_n,\tilde{a}_0,\tilde{a}_1,...,\tilde{a}_n\right)\ \ j=\overline{1,m}$ (structural identification) are determined, e.g. based on the method of sequential inclusion of regressors.

– Step 6. Based on the methods of expert assessments with the involvement of decision-makers, the object (an element of the chemical engineering system) is described and the term-set $T(X_i, Y_j)$ of fuzzy parameters is determined.

– Step 7. Constructing the MF of fuzzy parameters $\mu_{A_i}\left(\tilde{x}_i\right)$, $\mu_{B_j}\left(\tilde{y}_j\right)$. To construct an MF, e.g., the output parameters of an object, it was proposed to use the following formula:

$$\mu^p_{B_j}\left(\tilde{y}_j\right) = \exp\left(Q^p_{B_j}\left|\left(y_j - y_{mdj}\right)^{N^p_{B_j}}\right|\right). \quad (1)$$

Here and below, *p* is the quantum number; $Q^p_{B_j}$ is the parameter characterizing the degree of fuzziness; $N^p_{B_j}$ is the coefficient that makes it possible to more accurately approximate the MF graph; y^p_{mdj} is the fuzzy variable that more closely corresponds to the selected term. The $Q^p_{B_j}$ parameter value is identified when constructing the MF; the fuzzy variable y^p_{mdj}, exactly corresponding to the selected term is determined by the expression $\mu^p_{B_j}\left(y_{mdi}\right) = \max\limits_j \mu^p_{B_j}\left(y_j\right)$.

– Step 8. If the mode parameters and criteria, i.e., the input and output parameters of the CES element are fuzzy (linguistic variables), then the fuzzy mappings R_{ij} which determine the relationships between these linguistic variables $\tilde{x}_i$ and $\tilde{y}_j$. are formalized. Linguistic models are built with a transition to Step 10.

– Step 9. If the condition of Step 5 is fulfilled, that is, the input and mode parameters are clear, then values of the fuzzy coefficients $(\tilde{a}_0,\tilde{a}_1,...,\tilde{a}_n)$ of the models $\tilde{y}_j$ (parametric identification) the structure of which is identified in Step 5 are estimated and transition to Step 11 is made.

–Step 10. If the condition of Step 8 is satisfied, i.e., both the input and output parameters of the CES element are fuzzy, then based on the rules of compositional inference $B_j=A_i \circ R_{ij}$, fuzzy values of the object's output parameters are determined:

$$\mu^p_{B_j}\left(\tilde{y}^*_j\right) = \max_{x_i \in X_i}\left\{\min\left[\mu^p_{A_i}\left(\tilde{x}^*_i\right),\mu^p_{R_{ij}}\left(\tilde{x}^*_i,\tilde{y}_j\right)\right]\right\}, . \quad (2)$$

where $\mu^p_{B_j}\left(\tilde{y}^*_j\right)$ is the membership function of fuzzy output parameters on the *p*-th quantum. Clear, i.e., the numerical values of the output parameters of the object $\tilde{y}^{**}_j$, are determined from the set of fuzzy solutions (2) by the formula:

$$\tilde{y}^{**}_j = \arg\max_{\tilde{y}^*_j} \mu^*_{B_j}\left(\tilde{y}^*_j\right).$$

– Step 11. The adequacy of the model is checked. If the condition of adequacy, i.e. $S = |y_m - y_e| \le S_D$ is met, then the developed models are considered adequate and are recommended for use. In the given condition, S and S_D are the value of the criterion for assessing the adequacy and its permissible value, respectively; y_M and y_E are the values of output parameters obtained from the model (y_M) and the results of experiments (y_E). In this case, the values of the input parameters must be the same. Otherwise, the cause of inadequacy is found out and a return to appropriate steps is made to eliminate causes of inadequacy and achieve adequacy.

5. 2. Construction of mathematical models of the chemical engineering system of benzene production taking into account fuzziness of initial information

In accordance with Step 3.2 of the proposed algorithm, the models of CES of benzene production were established as nonlinear regression equations describing the dependence of particular criteria (yields of benzene, raffinate, and heavy aromatics) on operating parameters x_1, x_2, x_3:

$$f_1\left(x_1,x_2,x_3\right) = 0.099849x_1 + 0.020462x_2 - 0.76x_3 + \\ +0.000148x_1^2 + 0.000008x_2^2 - 0.032571x_3^2 + \\ +0.000046x_1x_2 + 0.000571x_1x_2 - 0.000585x_2x_3; \quad (3)$$

$$f_2\left(x_1,x_2,x_3\right) = \\ = 0.061562x_1 + 0.012615x_2 - 0.234286x_3 + \\ +0.000074x_1^2 - 0.000015x_2^2 + 0.013388x_3^2 + \\ +0.000009x_1x_2 + 0.001055x_1x_3 - 0.000180x_2x_3; \quad (4)$$

$$f_3\left(x_1,x_2,x_3\right) = 0.000000001 + 0.0418920x_1 - \\ -0.171690x_2 + 3.188570x_3 + 0.000630x_1^2 - \\ -0.00013x_2^2 + 0.136653061x_3^2 + 0.00006x_1x_2 + \\ +0.00718x_1x_3 - 0.00123x_2x_3. \quad (5)$$

Parameters of equations (3) to (5) were determined by means of the least square method (using the Regress multiple regression programs). The parameters x_4 (the proportion of sulfur) and x_5 (the proportion of aromatic hydrocarbons (HC) in the feedstock have a very weak effect on the values of $f_1(\mathbf{x})$, $f_2(\mathbf{x})$, $f_3(\mathbf{x})$, so they can be neglected.

For mathematical formalization of fuzzy constraints $\varphi_1(\mathbf{x})$, $\varphi_2(\mathbf{x})$, TFS methods were used with their representation as fuzzy regression equations. For parametric identification of models describing fuzzy constraints, the membership functions of the constraint upholding were constructed first using expression (1). Then, the fuzzy model was represented as a system of clear regression models using α sets, at α=0.5; 0.8; 1 which are more reliable points. After that, parameters of the obtained system of conventional regression models on the indicated α slices were identified using the least square method [29].

For example, fuzzy constraint $\varphi_1(\mathbf{x})$ "the average octane number of benzene $\tilde{\geq}102$" and the results of parametric identification will have the following form where the numerical values of regression coefficients of the corresponding α level are determined using the least square method.

$$\phi_1(x_2,\ldots,x_5)=\begin{pmatrix}0.5/0.0231+0.8/0.0233+\\ +1/0.0235+\\ +0.8/0.0237+0.5/0.0239\end{pmatrix}x_2-$$
$$-\begin{pmatrix}0.5/0.5823+0.8/0.5825+\\ +1/0.5828+0.8/0.58+0.5/0.5834\end{pmatrix}x_3-$$
$$-\begin{pmatrix}0.5/5{,}000+0.8/5{,}050+\\ +1/5{,}100+0.8/5{,}150+0.5/520\end{pmatrix}x_4+$$
$$+\begin{pmatrix}0.5/1.01+0.8/1.015+1/1.02+\\ +0.8/1.025+0.5/1.03\end{pmatrix}x_5+$$
$$+\begin{pmatrix}0.5/0.000014+0.8/0.000016+\\ +1/0.000018+\\ +0.8/0.00002+0.5/0.000022\end{pmatrix}x_2^2-$$
$$-\begin{pmatrix}0.5/0.01655+\\ +0.8/0.0166+1/0.01665+\\ +0.8/0.0167+0.5/0.01675\end{pmatrix}x_3^2-$$
$$-\begin{pmatrix}0.5/12{,}747+0.8/127{,}485+\\ +1/1{,}275+0.8/127{,}515+0.5/12{,}753\end{pmatrix}x_4^2+$$
$$+\begin{pmatrix}0.5/0.02443+0.8/0.02446+\\ +1/0.02448+\\ +0.8/0.02450+0.5/0.024530\end{pmatrix}x_5^2+$$
$$+\begin{pmatrix}0.5/0.00042+0.8/0.000450+\\ +1/0.000470+0.8/0.00049+\\ +0.5/0.00052\end{pmatrix}x_2x_5-$$
$$-\begin{pmatrix}0.5/145.680+0.8/145.7040+\\ +1/145.7140+0.8/145.7240+\\ +0.5/145.740\end{pmatrix}x_3x_4-$$
$$-\begin{pmatrix}0.5/0.00578+0.8/0.00580+\\ +1/0.0058+0.8/0.00582-\\ -0.5/0.00583\end{pmatrix}x_3x_5+$$
$$+\begin{pmatrix}0.5/48.00+0.8/50.00+1/51.00+\\ +0.8/52.00+0.5/54.00\end{pmatrix}x_4x_5\tilde{\geq}102.$$

Similarly, a fuzzy constraint "the sulfur content in benzene should be no more than 0.00005 %" is represented i.e. $\phi_2(x_2,\ldots,x_5)\tilde{\leq}0.00005$.

Since the membership functions of fuzzy coefficients usually are bell-shaped, i.e. Gaussian form (1), there are left (0.5 and 0.8) and right (0.8 and 0.5) values of α-levels. When constructing a membership function based on expert methods, it was this form of the membership function that turned out to more adequately describe the fuzzy ideas of experts. For the transition to clear numbers, a defuzzification process was performed [30]. To determine the effect of aromatic hydrocarbons in the reformate composition on the average octane number of benzene, linguistic models that implement the logical inference "the more aromatic hydrocarbons in the composition of the feedstock, the higher the average octane number of benzene" have been constructed based on the proposed method:

$$\text{if } \tilde{x}\in\tilde{A}_1, \text{then } \tilde{y}\in\tilde{B}_1,$$
$$\text{if } \tilde{x}\in\tilde{A}_2, \text{then } \tilde{y}\in\tilde{B}_2,$$
$$\text{else if } \tilde{x}\in\tilde{A}_3, \text{then } \tilde{y}\in\tilde{B}_3,$$

where $A_1=nz$, $B_1=nn$, $A_2=sr$, $B_2=nr$, $A_3=vs$, $B_3=vn$; $\tilde{A}_i$, $\tilde{B}_j$, $i=\overline{1,3}$; $j=\overline{1,3}$ are fuzzy subsets (nz for "low", nn for "below the norm", sr for "average", nr for "normal", vs for "high", vn for "above the norm" are linguistic values); $\tilde{y}$ are input and output linguistic variables describing operating parameters and criteria that assess the quality of the feedstock and the average octane number of benzene. The models depict the relationship between $\tilde{x}$ and $\tilde{y}$.

For multicriteria optimization in the control of the CES of benzene production, it is necessary to determine and select such values of the operating parameters x_1, x_2, x_3, x_4, x_5. By means of their change, it is possible to determine extreme values of the selected criteria $f_i(x)$, $i=\overline{1,m}$. In doing this, it is necessary to observe the process variable stable which makes it possible to realize the process in a stable and trouble-free mode ($x\in X$; $X=\{x\in\Omega, \phi_q(x)\tilde{>}b_q, q=1,2\}, x=[x^{\min},x^{\max}]$) [31].

5 .3. Statement of the optimization problem for the control of operating modes of a chemical engineering system in a fuzzy environment

The constraints $\varphi_1(\mathbf{x})$ and $\varphi_2(\mathbf{x})$ are fuzzy in the formulated problem of multicriteria optimization for controlling the operation modes of a CES of benzene production. Therefore, a fuzzy approach was used in the mathematical formulation of these constraints. Later, when solving this problem, the ideas of multicriteria assessment of alternatives, compromise schemes modified to work in a fuzzy environment were effectively applied.

Let us give a classification of the problems of multicriteria optimization as applied to the specifics of oil refining, petrochemical, and chemical industries. The following types of the problems under consideration can be distinguished:

– problems with clear target functions (criteria), clear control variables, clear control constraints, clear functional constraints (on target functions);

– problems with clear target functions, clear control variables, clear control constraints, and fuzzy functional constraints;

– problems with clear target functions, clear control variables, fuzzy control constraints, fuzzy functional constraints.

Other types of optimization problems in other combinations are possible. The problem of multicriteria optimization

in the control of the CES of benzene production of the second type is studied and solved there. Thus, the problem being solved is characterized by clear target functions, clear control variables, clear control constraints, and fuzzy functional constraints.

Formalization of the multicriteria optimization problem in the control of the CES operation modes in a fuzzy information environment.

Let $f(\mathbf{x})=(f_1(\mathbf{x}), f_2(\mathbf{x}), ..., f_m(\mathbf{x}))$ is the vector of partial control criteria that evaluates the operating modes, i.e., the CES operation quality. Values of these criteria depend on $\mathbf{x}=(x_1, x_2, ..., x_n)$, i.e., the vector of operating parameters [13, 32–36]. Assume that this dependence is described by mathematical models developed on the basis of the above method. Fuzzy constraints on quality indicators of objects can be described as $\phi_q(\mathbf{x})\tilde{\geq} b_q,\ \ q=\overline{1,L}$.

It is necessary to choose such values of operating parameters $x_1, x_2, ..., x_n$, which provide the best values of the vector of control criteria $f(\mathbf{x})=(f_1(\mathbf{x}), f_2(\mathbf{x}), ..., f_m(\mathbf{x}))$ when the specified fuzzy constraints are met. When selecting the operating modes, it is necessary to take into account the decision-maker preferences.

The mathematical statement of the problem.

A formalized control problem in multicriterial and fuzziness conditions can be written in the following statement:

$$\max_{x\in X} f_i(\mathbf{x}),\ \ i=\overline{1,m}; \tag{6}$$

$$X=\left\{\mathbf{x}\in\Omega, \varphi_q(\mathbf{x})\tilde{>} b_q, q=\overline{1,L}\right\}, \tag{7}$$

where $f_i(\mathbf{x}), i=\overline{1,m}$ are the partial control criteria with their values calculated by the models [9, 26, 37]; $\varphi_q(\mathbf{x}), q=\overline{1,L}$ are constraint functions that determine the admissible domain Ω of the multicriterial problem (6), (7); $b_q,\ q=\overline{1,L}$ are specified numbers which may be fuzzy.

This problem of multicriteria optimization of the CES operation modes is solved using the values of the operating parameters that provide the best values of the criteria that satisfy thedecision-maker.

Rewrite statement of the problem of multicriteria optimization (6), (7) in relation to control of the CES operating modes based on the TFS methodology.

Introduce the following designations:

$$\mu_0(\mathbf{x})=\left(\mu_0^1(\mathbf{x}),...,\mu_0^m(\mathbf{x})\right)$$

for normalized criteria $f_i(\mathbf{x}),\ i=\overline{1,m}$, that determine the quality of the CES operation taking values in the interval [0, 1]; $\mu_q(\mathbf{x}), q=\overline{1,L}$ are membership functions of upholding the fuzzy constraints $\phi_q(\mathbf{x})\tilde{\geq} b_q,\ q=\overline{1,L}$; $\gamma=(\gamma_1,...,\gamma_m)$, $\beta=(\beta_1,...,\beta_L)$ are respectively the weight vectors set by the decision-maker and determining mutual importance of criteria and constraints.

In order to adapt various compromise schemes to ensure operation with fuzzy information, it is possible to state various problems of multicriteria optimization in the control of the CES operating modes and develop methods for their solution. Such problems are stated there as problems of multicriteria fuzzy optimization (fuzzy mathematical programming) [13, 26, 38, 39].

In practice, when solving the problems under consideration, it is often sufficient to fulfill certain principles of optimality with a certain concession. We propose to use the principles of quasiminimax (for criteria) and ideal point (for constraints) modified for operation in a fuzzy environment.

Then the statement of the multicriteria optimization problem of control of the operating modes of the CES in a fuzzy environment is as follows:

$$\max_{x\in X}\mu_0^1(\mathbf{x}), \tag{8}$$

$$X=\left\{\begin{array}{l} x:\arg\max\limits_{x\in\Omega}\min\limits_{i\in I_0}\left(\gamma_i\mu_0^i(\mathbf{x})-\Delta_i\right)\wedge \\ \wedge\arg\left(\mu_q(\mathbf{x})\geq\min\|\mu(\mathbf{x})-\mu^u\|_D\right), \\ I_0=\{2,...,m\}, q=\overline{1,L}\end{array}\right\}. \tag{9}$$

In expression (9), $\|\mu(x)-\mu^u\|_D$ there is a metric that assesses the distance from the current solution of $\mu(\mathbf{x})$ to the ideal solution μ^u; $\mu^u=\left(\max\mu_1(\mathbf{x}),...,\max\mu_L(\mathbf{x})\right)$ is the coordinate of the ideal point (of solution). If the membership functions are normal, then $\mu^u=(1,...,1)$; Ω is the original set of definitions of the variables x, I_0 is the set of indices of the criteria transferred to the constraints.

In the statement (8), (9), when controlling modes of CES operation, the problem of maximizing the most important criterion with a priority 1 set by the decision-maker and experts is solved. In this case, the rest of the partial criteria are included in the constraints on the basis of the quasi-maximin principle taking into account the concessions introduced by the decision-maker and the degrees of meeting the fuzzy constraints are checked on the basis of the idea of the ideal point principle.

Let us consider another combination of using the principles of optimality: maximin (for criteria) and Pareto optimality (for constraints), in the statement and solution of the problem of multicriteria optimization in control of the CES operating modes. In this case, the original problem can be written in the following statement:

$$\max_{x\in X}\mu_0^1(\mathbf{x}), \tag{10}$$

$$X=\left\{\begin{array}{l}\arg\max\limits_{x\in\Omega}\min\limits_{i\in I_0}\left(\gamma_i\mu_0^i(\mathbf{x})\right)\wedge\arg\max\limits_{x\in\Omega}\wedge \\ \wedge\sum\limits_{q=1}^{L}\beta_q=1\wedge\beta_q\geq 0, I_0=\{2,...m\}, q=\overline{1,L}\end{array}\right\}. \tag{11}$$

In problems (10), (11), the main criterion with priority 1 is maximized. The remaining criteria are included in constraints according to the maximin (MM) principle and fuzzy constraints are taken into account based on the Pareto optimality (PO) principle.

5. 4. Development of a heuristic algorithm for solving the problem of a multicriteria optimization in a fuzzy environment

The following heuristic algorithm is proposed for solving the problem (10), (11).

The heuristic algorithm based on a combination of the principles of maximin and Pareto optimality (MM+PO):

1. Values of the weight coefficients for particular criteria are determined in the dialogue with the decision-maker $\mu_0^i(\mathbf{x}),\ i=\overline{1,m},\quad \gamma=(\gamma_1,...,\gamma_m),\ \sum\limits_{i=1}^{m}\gamma_j=1, \gamma_i\geq 0.$

2. Values of the weight coefficients for the constraints are determined in a dialogue with the decision-maker $\mu_q(\mathbf{x})$, $q=\overline{1,L}:\ \beta=(\beta_1,...,\beta_L),\ \sum\limits_{q=1}^{L}\beta_q=1,\ \beta_q\geq 0,\ q=\overline{1,L}.$

3. The number of steps $p_q,\ \ q=\overline{1,L}$ is specified for each q-th coordinate.

4. In order to change the coordinates of the vector β_q, the steps are determined by the expression $h_q=\frac{1}{p_q}$, $q=\overline{1,L}$.

5. A set of weight vectors $\beta^1, \beta^2, \ldots, \beta^N$,

$$N=(p_1+1)\times(p_2+1)\times\ldots\times(p_L+1)$$

is determined by varying the coordinates with a step h_q in the interval [0, 1].

6. A term-set is selected with the involvement of a decision-maker and experts and membership functions are constructed for fuzzy constraints $\mu_q(x)$, $q=\overline{1,L}$.

7. On the basis of the CES model, the problem of maximizing the main (first) criterion $\max_{x\in X}\mu_0^1(\mathbf{x})$ (10) on the set X which is determined from expression (11) is solved. The current solutions are determined: the values of operating parameters $x(\gamma,\beta)$, the values of the criteria $\mu_0^1(\mathbf{x}(\gamma,\beta))$, ..., $\mu_0^m(\mathbf{x}(\gamma,\beta))$ and the degree of upholding of fuzzy constraints $\mu_1(\mathbf{x}(\gamma,\beta))$, ..., $\mu_1(\mathbf{x}(\gamma,\beta))$.

8. The decision-maker analyzes the current decisions. If the current decisions do not satisfy the decision-maker, then values of the weight coefficients $\gamma_1,\ldots,\gamma_m$ and/or $\beta_1,\ldots,\beta_L$ are corrected and a transition back to Step 3 is made. Otherwise, the transition to the next Step 10 is made.

9. The search for solutions is stopped and optimal values, that is, ones selected by the decision-maker are derived, the final results which provide optimal modes for the CES control: optimal values of the mode (control) parameters $x^*(\gamma,\beta)$, that provide the best values of particular criteria $\mu_0^1(\mathbf{x}^*(\gamma,\beta)),\ldots,\mu_0^m(x^*(\gamma,\beta))$ and the maximum degree of upholding of fuzzy constraints $\mu_1(\mathbf{x}^*(\gamma,\beta)),\ldots,\mu_L(x^*(\gamma,\beta))$.

Thus, various statements of the multicriteria optimization problem have been obtained in controlling the CES operating modes in a fuzzy information environment. On the basis of various optimality principles (maximin and Pareto optimality) and the TFS methods, an effective heuristic algorithm for solving MM+PO was proposed.

5. 5. Implementation of the obtained study results in optimizing the operating modes of the chemical engineering system for benzene production

Let us consider statements and solutions of the problem of controlling the operating modes of the CES of benzene production at the Atyrau refinery as an example of implementation of the proposed fuzzy approach to solving the problem of multicriteria optimization when controlling the CES operating modes. Using the above study results and based on a modification of the maximin methods and the Pareto principle of optimality, the problem of multicriteria optimization of operating modes of the CES of benzene production can be formalized and formulated as follows:

Let us introduce the following designations:

$$\mu_0(\mathbf{x})=(\mu_0^1(\mathbf{x}),\mu_0^2(\mathbf{x}),\mu_0^3(\mathbf{x}))$$

for a normalized criterion (in the interval [0.1]) which evaluates the yield of benzene production by the CES; ($\mu_0^1(\mathbf{x})$ is benzene yield, $\mu_0^2(\mathbf{x})$ is raffinate yield, $\mu_0^3(\mathbf{x})$ is heavy aromatics yield); $\mu_1(\mathbf{x}),\mu_2(\mathbf{x})$ is MF of upholding of the fuzzy constraints, $\phi_q(x)\tilde{\geq} b_q$, $q=1,2$; $\gamma=(\gamma_1, \gamma_2, \gamma_3)$ and $\beta=(\beta_1, \beta_2)$ are weight vectors reflecting mutual importance of criteria and constraints.

Then the mathematical statement of the problem of multicriteria optimization when controlling the CES of benzene production based on problems (10), (11) can be written in the following form:

$$\max_{\mathbf{x}\in X}\mu_0^1(\mathbf{x}), \tag{12}$$

$$X=\left\{\begin{array}{l}\arg\max_{x\in\Omega}\min_{i\in I_0}\left(\gamma_i\mu_{0R}^i(\mathbf{x})\right)\wedge\arg\max_{x\in\Omega}\sum_{q=1}^{2}\beta_q\mu_q(\mathbf{x})\wedge\\ \wedge\sum_{q=1}^{2}\beta_q=1\wedge\beta_q\geq 0, I_0=\{\{2,3\}\}, q=\overline{1,2}\end{array}\right\}. \tag{13}$$

In the statement (12), (13), $\wedge$ is a logical AND which means that all the statements connected by it are true; $X=\mu_{OR}^i$ are the constraints for the criteria $\mu_0^i(\mathbf{x}), i=2,3$. introduced by the decision-maker. Variation of the values of weight coefficients of the local criteria γ_1, γ_2, γ_3 and the constraints β^1, β^2 gives a family of solutions to the problem (12), (13) among which optimal values of the operating parameters $x^*(\gamma,\beta)$, are chosen by the decision-maker to ensure maximum values of the criteria without violating the constraints.

To solve the set problem of multicriteria optimization when controlling operating modes of a CES of benzene production (12), (13), use a combination of modified methods of maximin (MM) and Pareto optimality (PO).

Let us concretize the MM+PO algorithm for solving the problem (12), (13):

1. In a dialogue with the decision-maker, values of weight coefficients of partial criteria were determined and entered: $\mu_0^i(x)$, $i=\overline{1,3}$, $\gamma=(\gamma_1,\gamma_2,\gamma_3)$, $\sum_{i=1}^{2}\gamma_i=1, \gamma=(0.7,0.2,0.1)$.

2. In a dialogue with the decision-maker and the experts, values of the weight coefficients for constraints were determined: $\mu_q(\mathbf{x})$, $q=\overline{1,3}$: $\sum_{q=1}^{L}\beta_q=1$, $\beta_q\geq 0$, $q=\overline{1,2}$: $\beta=(0.7,0.3)$.

3. The decision-maker has given p_q, $q=1,2$, i.e. the number of steps in the coordinates: $p_1=5$; $p_2=2$.

4. The values of steps $h_q=\frac{1}{p_q}$, $q=1,2$ for changing the coordinates of the weight vector were calculated: β_q: $h_1=\frac{1}{p_1}=\frac{1}{5}=0.2$; $h_2=\frac{1}{p_2}=\frac{1}{2}=0.5$.

5. Weight vectors β^1, β^2, ..., β^N, $N=(5+1)\mathbf{r}(2+1)=18$ were determined by varying the coordinates in intervals of [0, 1] with the step h_q, $q=1,2$.

6. The term-set was determined and MFs for upholding of constraints $\mu_q(\mathbf{x})$, $q=1,2$. were constructed.

The problem is described by two fuzzy constraints: "the average octane number of benzene $\tilde{\geq}102$" and "the proportion of sulfur in the composition of benzene $\tilde{\leq}0.00005$ %". To describe these fuzzy constraints, the following term-set was determined: $T(X, Y)$={low, below average, average, above average, high}. With the use of the reduced term set $T(X, Y)$ based on formula (1), MFs were constructed that describe the degrees of upholding of fuzzy constraints:

$$\mu_1^1(\mathbf{x})=\exp((0.5|y_4-97)0.60|);$$

$$\mu_1^2(\mathbf{x})=\exp((0.5|y_4-100)0.55|);$$

$$\mu_1^3(\mathbf{x})=\exp((0.5|y_4-102)0.50|);$$

$$\mu_1^4(\mathbf{x})=\exp((0.5|y_4-104)0.55|);$$

$$\mu_1^5(\mathbf{x})=\exp((0.5|y_4-107)0.60|);$$

$$\mu_2^1(\mathbf{x}) = \exp((0.3\,|\,y_5 - 0.000005)0.15\,|);$$

$$\mu_2^2(\mathbf{x}) = \exp((0.3\,|\,y_5 - 0.000020)0.12\,|);$$

$$\mu_2^3(\mathbf{x}) = \exp((0.3\,|\,y_5 - 0.000050)0.10\,|);$$

$$\mu_2^4(\mathbf{x}) = \exp((0.3\,|\,y_5 - 0.000080)0.12\,|);$$

$$\mu_2^5(\mathbf{x}) = \exp((0.3\,|\,y_5 - 0.000100\,)0.15\,|),$$

where $\mu_1^p(\mathbf{x})$, $\mu_2^p(\mathbf{x})$, $p=\overline{1,5}$ are the MFs describing the degree of upholding of fuzzy constraints for each quantum p on the average octane number of benzene $(\mu_1^p(\mathbf{x}))$, and the proportion of sulfur in the composition of benzene $(\mu_1^p(\mathbf{x}))$, y_4 and y_5 are numerical values of fuzzy indicators of quality of benzene obtained on the basis of a set of level α. The remaining coefficients were considered when describing the formula (1).

7. Based on the above models (3) to (5) and fuzzy constraints describing the dependence of particular criteria on operating parameters: x_1, x_2, x_3, x_4, x_5, the problem $\max_{\mathbf{x}\in X}\mu_0^1(\mathbf{x})$, (12) was solved on the set X (13). The criteria were maximized on the set X taking into account the importance coefficients, which are defined in P. Current solutions were defined: the values of operating parameters $x(\gamma,\beta)$ and corresponding values of the partial criteria $\mu_0^1(x(\gamma,\beta),\mu_0^2(x(\gamma,\beta),\mu_0^3(x(\gamma,\beta)$, and the degree of upholding of fuzzy constraints $\mu_1(x(\gamma,\beta))$, $\mu_2(x(\gamma,\beta))$. The most suitable method for solving the problem can be applied here. In this case, the penalty function method modified for working in a fuzzy environment was used.

Based on the penalty function method, the original problem of conditional optimization (12), (13) is replaced by an unconstrained optimization problem of the following form:

$$F(x_1, x_2, x_3)=f_1(x_1, x_2, x_3)+H(x_1, x_2, x_3),$$

where the penalty function $H(x_1, x_2, x_3)=\sum\alpha_i X$.

Explicit forms of the function $f_1(x_1, x_2, x_3)$ were presented in expression (3) and the constraint X in expression (13).

Further, the well-known algorithm of the method of penalty functions [40] implemented on the Manager software package was used.

8. The obtained solutions are presented to the decision-maker. If the current results do not satisfy the decision-maker, then he corrects the values γ_1, γ_2, γ_3 and (or) β_1, β_2, and return to p. 2 is made. If the decision-maker is satisfied, the transition to p. 10 is made. In this case, the decision-maker has chosen the solutions that satisfied him after the 5th cycle and these results were entered in Table 1 (Optimization results).

9. Stopping the search for a solution, determination of the final solutions satisfying the decision-maker that ensure optimal mode for the CES of benzene production: optimal values of operating parameters

$$x^* = (x_1^*(\gamma,\beta), x_2^*(\gamma,\beta), x_3^*(\gamma,\beta), x_4^*(\gamma,\beta), x_5^*(\gamma,\beta));$$

maximum values of partial criteria

$$\mu_0^1(x^*(\gamma,\beta)),\mu_0^2(x^*(\gamma,\beta)),\mu_0^3(x^*(\gamma,\beta))$$

and the maximum degrees of upholding of fuzzy constraints $\mu_0^1(x^*(\gamma,\beta)),\mu_0^2(x^*(\gamma,\beta)),\mu_0^3(x^*(\gamma,\beta))$ (Table 1).

The results of the decision-maker's choice of final decisions i.e. the results obtained in p. 9 of the algorithm are presented in the penultimate column of Table 1. For comparison with the obtained results, Table 1 also contains the results of optimization by means of the deterministic method [41] and the real data taken from the operating CES of benzene production at the Atyrau refinery.

Table 1

Comparison of the results of optimization of the CES operating modes obtained using the deterministic method, the proposed algorithm, and real values

Values of the control and constraint criteria	Deterministic method [41]	Proposed method	Real values
Benzene yield from the benzene column, thousand t. Criterion $f_1(\mathbf{x})$	133	134.45	133.5
Raffinate yield from the benzene column, thousand t. Criterion $f_2(\mathbf{x})$	82	82.4	82.2
Heavy aromatics yield from the rectification column, thousand t. Criterion $f_3(\mathbf{x})$	450	450	450
MF of upholding fuzzy constraint. The mean octane number of benzenes must be ≥102–$\mu_1(\mathbf{x}^*(\gamma, \beta))$	–	1.0	–
MF of upholding of the fuzzy constraint. Sulfur content in benzene must be $\tilde{\leq}$ 0.00005 % – $\mu_1(\mathbf{x}^*(\gamma, \beta))$	–	1.0	–
Optimum values of mode parameters $\mathbf{x}^* = (x_1^*, x_2^*, x_3^*, x_4^*, x_5^*)$			
x_1^*: raw material, reformate input, thousand t	746	746·10	746
x_2^*: temperature in the benzene column, °C	150	150	150
x_3^*: pressure in the benzene column, kPa	37	35	36
x_4^*: portion of sulfur in the raw material, %	0.00005	0.00005	0.00005
x_5^*: portion of aromatics HC in the raw material, %	50	50	50

Note: In the deterministic approach and in practice, the degrees of upholding of fuzzy constraints are not determined, therefore, (–) was entered in the corresponding columns of Table 1. Real values of the parameters in Table 1 correspond to the values of technological parameters of one of the modes of the benzene production unit at the Atyrau refinery

Table 1 shows the results of optimization of operating modes of the CES of benzene production according to the deterministic method according to the proposed algorithm and real production data in the optimal mode. The data presented make it possible to draw a conclusion about the advantages of the proposed fuzzy approach to optimization of complex chemical engineering systems operating in a fuzzy environment.

6. Discussion of the results obtained in the study of modeling and optimization of the benzene production processes

The main criterion having priority 1 is maximized in the formulated problem of multicriteria optimization for con-

trolling the CES operating modes (10), (11). The remaining local criteria are introduced into the constraints according to the maximin principle, and fuzzy constraints are taken into account based on the Pareto optimality principle. The developed heuristic algorithm of solving the optimization problem in a fuzzy environment (10), (11) is based on a combination of the principles of maximin and Pareto optimality (MM+PO). In this case, the maximin principle is applied for criteria $\mu_0^i(\mathbf{x}), i=\overline{1,m},$ and the principle of Pareto optimality is applied to fuzzy constraints $\mu_q(\mathbf{x}),\ q=\overline{1,L}.$

As a result of solving a concrete problem of multicriteria optimization for controlling the operating modes of the CES of benzene production (12), (13) on the basis of the proposed fuzzy algorithm, better results were obtained in comparison with the results of the deterministic approach.

As a result of the analysis of the data given in Table 1, the following features and advantages of the fuzzy approach can be emphasized:

1. In comparison with the deterministic method, the proposed heuristic algorithm MM+PO makes it possible to solve the initial problem with fuzzy constraints without first transforming them into a deterministic version. According to some indicators, it provides better results.

2. When solving a multicriteria problem in a fuzzy formulation, adequacy of solution improves, since fuzzy information (knowledge, experience of decision-makers, and experts) is additionally used which makes it possible to adequately describe the real situation without idealization.

3. The MM+PO algorithm makes it possible to define the membership function, that is, the degree of upholding of fuzzy constraints. For example, $\mu_1\left(x^*(\gamma,\beta)\right)$ and $\mu_2\left(x^*(\gamma,\beta)\right)$, provide a solution to a problem with fuzzy constraints which often arise in production conditions.

4. It is possible to find a compromise solution between quantity and quality of products based on the proposed heuristic method in the process of solving a problem with the help of a decision-maker.

In well-known studies, statements of such problems in a fuzzy environment of the form (6), (7), and methods of their solution are mainly considered in relation to single-criterion cases: there is no flexibility in taking into account the decision maker's preferences. Besides, the initial fuzzy problem is replaced by a system of equivalent deterministic problems at the stage of making a statement with the use of sets of level α which may lead to the loss of the main part of the collected fuzzy information [12, 14, 19, 43].

It is often occurred that fuzzy information in a form of fuzzy opinions and judgments of specialists and basic initial information is more familiar and basic information for decision-makers in real conditions in the case of multicriteria optimization of the CES control. At the same time, conversion of initial fuzzy information into clear information often fails or turns out to be impractical. In these conditions, to effectively solve the problem under consideration, it is necessary to develop and apply heuristic methods based on the involvement of decision-makers and adapted to the procedures of human decision-making on control. That is, the problem of optimization has to be posed and solved in an environment of fuzzy information, without converting fuzzy problems to a system of deterministic problems. Therefore, a fuzzy approach based on the heuristic method was proposed to solve the problems of multicriteria optimization when controlling the CES operating in a fuzzy environment. The proposed heuristic method uses modified compromise schemes adapted to the use of fuzzy information.

In practice, in order to improve product quality, it will be necessary to reduce the volume of the product output. Therefore, the statement of the problem of maximizing the volume of benzene yield while simultaneously improving its quality is incorrect. In this case, there can be two options for a correct problem statement:

1. Maximization of the product output with a provision of quality indicators not less than the specified values, that is, introduction and consideration of constraints on quality.

2. Maximum improvement in the product quality with the provision of a specified output volume, that is, introduction and consideration of constraints on the product output volume.

The results given in Table 1 show the effectiveness of the proposed heuristic algorithm of solving the problem of controlling the CES operating modes in a fuzzy statement. This is substantiated by comparison with the results of known methods [40]. The proposed heuristic approach shows not worst results for all indicators and the results were improved in the benzene and raffinate yield.

In addition, the proposed heuristic algorithm MM+PO enables taking into account the fuzzy constraints and the degree of upholding of fuzzy constraints. As can be seen from Table 1, full implementation of fuzzy constraints is ensured, i.e., the membership functions are equal to 1: $\mu_1\left(x^*(\gamma,\beta)\right)=1;$ $\mu_2\left(x^*(\gamma,\beta)\right)=1.$

The following can be considered as the method limitation inherent to this study:

– the need for experienced experts and decision-makers in subject matters related to the problem being solved;

– considerable time and other costs required to organize, conduct and formalize the results of expert assessment;

– solution adequacy depends on the quality and correctness of expert information, experience, and intuition of decision-makers involved in the problem-solution process.

The main disadvantages of the proposed approach to solving the problem of multicriteria optimization include the complexity of constructing a membership function that adequately describes fuzzy parameters and some difficulties met by decision-makers in the process of choosing a solution. In the long term, these difficulties can be eliminated by developing a special system for constructing the membership functions and training, teaching the decision-maker to the decision-making process using the proposed technology.

Further development of this study can be based on maximum automation and algorithmization of the technology for searching the best solution. In this case, difficulties may arise associated with the mathematical formalization of a non-structured or difficult-to-structure decision-making problem as well as carrying out active experiments at an operating industrial chemical engineering system.

7. Conclusions

1. An algorithm for constructing CES models using the available information of different nature has been developed, main points of the method were given and described. The developed algorithm is based on the methodology of system analysis and makes it possible to construct models of individual elements of the technological system based on available information of diverse nature. In practice, the following may be available depending on the level of knowledge about various units:

– theoretical information (for constructing deterministic models);

– statistical information (for constructing statistical models);

– fuzzy expert information used in the development of fuzzy, linguistic models of the object.

In a case of insufficiency of the listed types of information for construction of the corresponding models, a hybrid model can be constructed based on the combination of initial information of various types.

2. Mathematical models of the benzene column of the benzene producing CES were constructed taking into account the fuzziness of initial information. The constructed models have a structure of nonlinear regression and fuzzy regression equations which are identified based on the method of sequential inclusion of regressors. Parameters of the developed models were identified using the modified least square method and the Regress program.

3. The mathematical statement of the multicriteria optimization problem for the control of the CES operating modes in a fuzzy information environment has been formulated. Formalization and statement of the problem are based on the methods of expert assessment and theories of fuzzy sets.

4. A heuristic algorithm has been developed for an efficient solution to the posed problem of multicriteria optimization in a fuzzy environment. An algorithm was developed based on the combined use of the maximin principles and Pareto optimality which were adapted to work in a fuzzy environment.

5. The study results were implemented in the development of mathematical models of the benzene column and in optimization of operating modes of benzene producing CES. As a result of the practical application of the research results, the effectiveness of the proposed fuzzy approach was shown when optimizing the operating modes of ta benzene producing CES based on constructed models. The obtained results make it possible to improve output variables: by 1.45 thousand t or 1.1 % for target benzene yield (y_1), by 0.4 thousand t or 0.49 % for the volume of raffinate yield (y_2) under the conditions of fuzzy constraints on benzene quality. In addition, the proposed approach makes it possible to assess the degree of upholding of fuzzy constraints.

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