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HEURISTIC APPROACH TO MULTI-CRITERIA OPTIMISATION OF A MODEL BASED DELAYED COKING PROCESS IN FUZZY ENVIRONMENT

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Abstract. Optimization tasks in many technological processes are inherently multidimensional and often characterized by uncertainty and fuzziness. This study focuses on the development and application of a method for solving multi-criteria optimization problems under such fuzzy conditions, using the delayed coking process as a case study. Main Results: A heuristic method has been developed by combining and modifying the principles of the main criterion and ideal points to address multi-criteria optimization in a fuzzy environment. Traditional methods for solving fuzzy optimization problems typically involve converting the initial fuzzy problem into a series of crisp (deterministic) problems using level sets. Scientific Novelty: The novelty of the proposed heuristic approach lies in its ability to formalize fuzziness and solve the original problem directly in the fuzzy domain, without transforming it into a set of crisp sub-problems. This leads to more accurate and practically applicable solutions in fuzzy environments. Practical Value: The proposed method can be effectively applied to optimize the operational parameters of complex industrial processes where uncertainty is a significant factor. Results: The optimization results for the delayed coking process demonstrate the advantages of the proposed fuzzy approach compared to traditional methods. This multi-criteria fuzzy optimization method enables more effective decision-making by leveraging available fuzzy information to its fullest extent.

Keywords: Delayed coking process, fuzzy information, principles of optimality, decision maker, heuristic method, delayed coking unit.

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БАЯУ КОКСТЕУ ПРОЦЕСІН АЙҚЫН ЕМЕС ОРТАДА КӨПКРИТЕРИЙЛІ ОПТИМИЗАЦИЯЛАУДЫҢ ЭВРИСТИКАЛЫҚ ТӘСІЛІ

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Аннотация. Өндірісте көптеген технологиялық процестерін оптисмизациялау есептері практикада көп өлшемді болып табылады. Бұл жұмыстың мақсаты кейбір технологиялық параметрлердің айқын еместігінен белгісіздік жағдайында баяу кокстеу процесінің мысалында, өндірістік күрделі технологиялық процестерді көпкритерийлі оптимизациялау есептерін зерттеу және шешу болып табылады. Негізгі нәтижелер: негізгі критерий мен идеалды нүктелер принциптерін модификациялау және біріктіру негізінде айқын емес ортада көпкритерийлік оптимизациялау есептерін шешудің эвристикалық тәсілі құрылды. Айқынсыздықта оптимизациялау есептерін шешудің белгілі тәсілдері бастапқы айқын емес есепті көптеген α деңгейлерге негізделген айқын есептер жиынтығына түрлендіруге негізделген. Ғылыми жаңалығы. Көпкритерийлі оптимизациялау есептерін шешудің ұсынылған эвристикалық тәсілінің ғылыми жаңалығы бастапқы айқын емес есеп айқын есептер жиынтығына айналдырмай, анық емес ортада тұжырымдалып, шешілетін

болады. Практикалық құндылық. Нәтижелердің практикалық құндылығы, алынған нәтижелер сипатталатын күрделі өндірістік объектілердің жұмыс режимдерін оптимизациялау есептерін шешу үшін іс жүзінде түрлі өндіриситік салаларында қолданыла алады. Нәтижелері. Баяу кокстеу процесін оптимизациялау нәтижелері белгілі тәсілдердің нәтижелерімен салыстырғанда ұсынылған айқын емес тәсілдің артықшылықтарын растайды. Ұсынылған эвристикалық тәсіл және белгілі детерминирделген тәсілдер негізінде анық емес ортада баяу кокстеу процесін көпкритерийлі оптимизациялау есебін шешу нәтижесінде эвристикалық тәсіл сапа көрсеткіштері қажетті деңгейде кокс көлемін сағатына 2,6 тоннаға арттыруға мүмкіндік беретіні анықталды. Бұл коксты сатудан айтарлықтай экономикалық тиімділік алуға мүмкіндік береді. Сонымен қатар, ұсынылған эвристикалық тәсіл белгілі тәсілдермен ескерілмеген айқын емес шектеулердің талаптарын ескеруге де мүмкіндік береді.

Түйін сөздер: баяу кокстеу процесі, айқын немес ақпарат, оптимизациялау принциптері, шешім қабылдаушы тұлға, эвристикалық тәсіл, баяу кокстеу қондырғысы.

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ЭВРИСТИЧЕСКИЙ МЕТОД МНОГОКРИТЕРИАЛЬНОЙ ОПТИМИЗАЦИИ ПРОЦЕССА ЗАМЕДЛЕННОГО КОКСОВАНИЯ В НЕЧЕТКОЙ СРЕДЕ

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Аннотация. Задачи оптимизации многих технологических процессов производств на практике являются многомерными и часто характеризуются нечеткостью некоторых важных параметров, описывающих качества работы производственных объектов. Целью данной работы является исследование и решение задач многокритериальной оптимизации сложных технологических процессов производства на примере процесса замедленного коксования в условиях неопределенности из-за нечеткости некоторых параметров процесса. К основным результатам исследования относятся: разработанный эвристический метод решения многокритериальной задачи оптимизации в нечеткой среде на основе модификации и сочетания принципов основного критерия и идеальных точек. Научная новизна предложенного эвристического метода решения задачи многокритериальной оптимизации в нечеткой среде заключается в формализации нечеткости, постановке и решения исходной задачи в нечеткой среде, не преобразуя к набору четких задач. Практическая ценность результатов в том, что полученные результаты могут быть эффективно применены на практике для решения задачи оптимизации режимов работы сложных производственных объектов различных отраслей, которые характеризуются нечеткостью. Результаты оптимизации процесса замедленного коксования подтверждают преимущества предложенного нечеткого подхода по сравнению с результатами известных подходов. Предлагаемый многокритериальный метод нечеткой оптимизации позволяет принимать более эффективные решения в нечеткой среде, максимально используя доступную нечеткую информацию. В результате решения задач многокритериальной оптимизации процесса замедленного коксования в нечеткой среде на основе предложенного эвристического метода и известными детерминированными методами установлено, что эвристический метод позволяет увеличить объем кокса с требуемыми качественными показателями на 2.6 тонна час.

Ключевые слова: процесс замедленного коксования, нечеткая информация, принципы оптимальности, лицо, принимающее решения, эвристический метод, установка замедленного коксования.

Introduction. Currently, a more promising direction for the development of oil refineries in Kazakhstan is to increase the depth of oil refining through deep oil refining processes, including the processing of fuel oils and tar sands and the production of petroleum coke and additional petroleum products. Technological processes of delayed coking take place at Delayed Coking Unit (DCU) of refineries. These processes are intended for the production of high quality petroleum petroleum coke and additional petrol, light and heavy gasoil by deep processing of heavy oil refining residues (tar, fuel oil). The DCU delayed coking process is the most efficient technology for the production of high-quality petroleum coke and additional petroleum products, for which there is a great demand in the market.

The main products of DCU are petroleum coke obtained from coke reactors, as well as gas, petrol, light and heavy gas oils produced in the main rectification column. The delayed coking process takes place in coking reactors at high temperatures and pressures for more than two dozen hours. From the coking reactors, in addition to petroleum coke, which is the target product, petroleum product vapours are released and sent to the main DCU rectification column, where petrol, light and heavy gasoil are produced.

The problem of solving these optimisation problems in addition to multicriteria is complicated by the fact that they are also characterised by fuzziness, since some elements of the problem are described fuzzily. In these cases, it is necessary to develop and apply heuristic methods based on the use of fuzzy information from the decision maker (DM), subject matter experts and their creativity to solve such multi-criteria optimisation problems in a fuzzy environment. Fuzzy information in this case represents the knowledge, experience and intuitions of the DMs and experts expressed in natural language. Let us present the results of the analysis of the research devoted to the issues of modelling and multi-criteria optimization of DCU operation modes and other facilities Ahmadlouydarab and others in the article (Ahmadlouydarab, et al., 2023) carried out an accurate mathematical correlation for estimation of coke yield at DCU. The authors of the works (Assanova, et al., 2023; Borges, et al., 2015) investigated the issues of mathematical modeling of DCU operation. These works develop deterministic models that are based on fundamental laws and are universal. But in practice very often problems of uncertainty arise due to the probabilistic and/or fuzzy nature of the input data required to develop such models. Even though it is theoretically possible to measure them indirectly, the procedure for measuring them in practice is often not economically feasible. Therefore, such production parameters and metrics are usually estimated fuzzily, in the natural language of DMs and subject matter experts.

In the monograph, Statnikov (Statnikov, et al., 2005) and others identified mathematical models of complex objects characterized by stochastic data. Shakeri Z, Douglas, Wen and other authors in (Shakeri, et al., 2021; Wen, et al., 2018) have explored and proposed approaches to developing models of complex objects based on available statistical data based on probabilistic methods. These approaches are more applicable to the development of models and optimisation of real production objects in practice, but they are not applicable under conditions of uncertainty due to the fuzziness of the initial data, when the axioms of probability theory are not fulfilled. In this regard, this work uses the methods of developing fuzzy models proposed by us in research (Orazbayev, et al., 2023; Orazbayev, et al., 2022) based on the fuzzy modeling studied in the works of the authors (Aliev, et al., 2018; Ali, et al., 2001).

Many works have been devoted to methods of multi-criteria optimization of parameters and operating modes of various objects based on their models, for example. In the research of Brans, Saber and others, a review and analysis of multicriteria optimization methods for solving various problems was carried out. The authors of investigated the issues of multicriteria optimisation of dynamic systems using predictor-corrector methods and dynamic object model. Multi-criteria optimization based on the method of studying the parameter space in engineering is proposed in the work of Statnikov and Matusov. Interactive methods of multicriteria optimization have been investigated and compared based on empirical experiments in.

In an approach to to multi-criteria optimization based on evolutionary methods and genetic algorithms has been investigated. In particular, in the studies of Coello, He and others, Evolutionary multi-objective optimization was analyzed and a method of evolutionary multi-purpose optimization based on Generative Adversarial Networks was proposed. A new multiobjective evolutionary algorithm based on the Pareto principle and an approach to evolutionary multicriteria optimization based on metamodels and methods of multicriteria decision-making are proposed respectively in.

Genetic algorithms and their application issues for solving multi-criteria optimisation problem are discussed in, and Lu and Yen proposed a multi-criteria genetic algorithm based on rank density in. Deb and others in proposed a fast and elitist multiobjective genetic algorithm using a non-dominant multi-criteria sorting-based expert Advisor, which allows to increase the speed of searching for optimal solutions. Features of the formulation and generalization of heretic algorithms for multicriteria optimization: discussed in. Although all the main issues of multi-criteria optimisation based on mathematical models and search optimisation have been investigated in the above analysed papers, but the issues of multi-criteria optimisation in fuzzy environment have not been considered.

In the works of Aliev, Zaichenko, Dymova and others, methods of multicriteria fuzzy optimization based on fuzzy/stochastic approaches and sets of level α of fuzzy set theory are investigated. And in, the issues of using the fuzzy optimization method in decision-making are considered. In these works, the effectiveness of the solutions obtained based on the methods of the proposed methods in a fuzzy environment is demonstrated. But since the outlined multi-criteria optimisation methods are based on a set of level α, some of the original fuzzy information representing the experience, the knowledge and intuitions of the DMs and experts, is lost when converting the fuzzy problem to a set of crisp problems. This will lead to reduced decision adequacy when solving manufacturing problems in a fuzzy environment. Such a situation motivated this study, which aims to develop a fuzzy approach to solve a multi-criteria fuzzy problem without converting the original fuzzy problem to crisp problems. The purpose of this study is to develop a heuristic approach to solving multi-criteria fuzzy optimisation problems, allowing maximum use of experience, knowledge and intuition of the DMs and experts, providing high adequacy of the obtained solutions in a fuzzy environment. In addition, based on the developed heuristic method, the problem of multi-criteria optimisation of delayed coking process in DCU Atyrau refinery in fuzzy environment will be solved. To achieve the stated goal, the following research tasks are set and solved:

− Formalisation and formulation of multi-criteria optimisation problem in fuzzy environment on the basis of modification of various optimality principles to work in fuzzy environment;

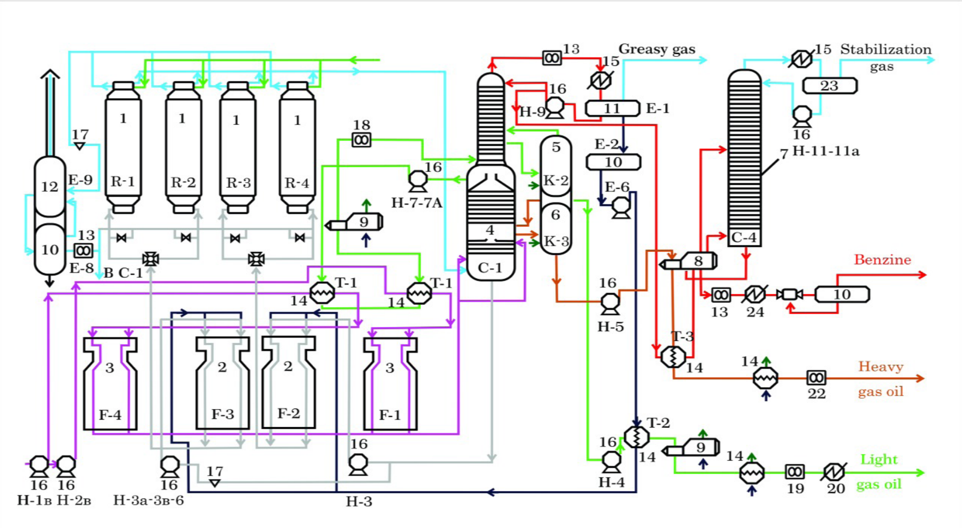
− development of an approach and a specific heuristic method for solving the set multi-criteria optimisation problem in a fuzzy environment;

− solution of the set problem of multi-criteria optimisation of the delayed coking process on the basis of the developed heuristic method and models developed taking into account the fuzziness of initial data.

The developed heuristic method for solving a multi-criteria optimisation problem in a fuzzy environment makes it possible to use DMs' and computational capabilities to iteratively improve and identify efficient solutions taking into account DMs' preference.

Materials and methods. The object of research is DCU model 21-10/6 of Atyrau refinery, designed for production of high quality petroleum coke and other petroleum products from tar and the quality of its work is evaluated by many criteria. Some important parameters, indicators characterising the qualities of manufactured products in production conditions are not directly measured, but are estimated by DMs and specialists in a fuzzy way in natural language. Therefore, the development of models of the main units and solving the problems of multi-criteria optimisation of the operating modes of the object have to be implemented taking into account the fuzziness of some part of the initial information, representing the experience, knowledge and intuition of DMs and expert specialists.

The flow diagram of the DCU 21-10/6 operated at Atyrau refinery is shown in Figure 1.



The main units of the DCU are as follows: 1—coking reactors; 2—secondary raw material heating furnaces; 3—primary raw material heating stoves; 4—the main rectification column.
Figure 1. Technological scheme of the DCU 21–10/6 of Atyrau refinery.

The main units of DCU 21-10/6 include coke reactors R-1, R-1 и R-3, R-4 operating in parallel, main rectification column C-1, primary F-1, F-4 and secondary F-2, F-3 heating furnaces. The delayed coking process on the DCU 21-10/6 proceeds as follows. The tar, which is the feedstock, is heated in primary feedstock furnaces (F-1, F-4) to the required temperature and is fed to the lower part of the main distillation column C-1. In C-1 the distillation process takes place and tar together with vapours of oil products from coking reactors, depending on boiling point, are divided into: gases; petrol; light and heavy gas oils and residues. The residues from the bottom of the column are heated in secondary feedstocks (F-2, F-3) and fed into coking reactors (R-1–R-4), where the delayed coking process takes place and petroleum coke is produced. In addition to coke, R-1–R-4 releases vapors of petroleum products sent to the C-1 rectification column.

The quantity and quality of coke and other commercial products of DCU depend on the conditions of the processes, on the operating modes, i.e. on the values of input and operating parameters of the main units of the plant. The problem of optimisation of delayed coking process at DCU is multi-criteria and fuzzy, since the quality of coke reactor operation is evaluated by several criteria, such as coke and oil vapour volumes and coke quality parameters. This problem also has a vector of constraints on the values of the regime parameters and on the quality indicators of coke, which are not directly measured, in production are estimated fuzzily according to the standard and with the participation of specialists.

In order to optimise the process of delayed coking in DCU coking reactors to obtain the maximum volume of coke with the required quality parameters, it is necessary to develop mathematical models of these reactors. The developed models should describe dependences of volume and quality indicators of produced coke on input and mode parameters of coking reactors. Since the quality indicators of coke (ash content and volatility of coke) are estimated in a fuzzy way with the participation of DMs and specialists will have to develop fuzzy models that take into account the influence of input, mode parameters of the coking process on coke quality. To optimise the coking process we use fuzzy models of ash content and coke fugacity estimation from the volume of raw material, temperature and pressure of coking reactors, coking index of raw material and recirculation coefficient developed by us in. These models are developed by us on the basis of the system method proposed in the above paper, which allows us to synthesise fuzzy and other types of models of interconnected units of the technological system on the basis of available fuzzy and other data.

A multi-criteria optimisation problem in a fuzzy environment shall be considered as an optimisation problem under conditions of a vector of criteria and several constraints in which all or some elements (criterion, constraints, weight coefficients) are fuzzy. In a general form, the problem of multi-criteria otimisation of the delayed coking process in a fuzzy environment for the solution in a fuzzy environment can be written in the following form:

$$\max_{x \in X} \mu_C^i(x), i = \overline{1, m}, \quad (1)$$

$$X = \left\{x: \arg\max_{x \in X} \mu_q(x), q = \overline{1, L}\right\} \quad (2)$$

where $\mu_R^i, i = \overline{2,m}$ – normalised local criteria' that take values in the interval [0,1] (coke and oil vapour yield), the values of which are determined on the basis of models; $x = (x_1, \dots, x_n)$ – vector of input, mode parameters of coke reactors, influencing the process of delayed coking; X - admissible area of the solution; $\max_{x \in X} \mu_q(x), q = \overline{1,L}$ – membership functions evaluating the degrees of fulfilment of fuzzy constraints on coke quality indicators .

The solution to this multi-criteria optimisation problem with fuzzy constraints is the values of input, mode parameters $x = (x_1, \dots, x_n)$ maximising the criteria $\mu_C^i(x), i = \overline{1,m}$ under the condition of fuzzy constraints and satisfying DMs.

The obtained general formulation of the multi-criteria optimisation problem (1)−(2) is incorrect because it requires to maximise *m* criteria at a single point and when solving production optimisation problems it is impossible to find solutions in which several conflicting criteria will be optimal at a single point. Therefore, to ensure the correctness of multi-criteria optimisation problem statements in fuzzy environment, we propose an approach based on the modification of various trade-off schemes, optimality principles for fuzziness. For example, by modifying the principles of principal criterion and Pareto optimality for fuzziness, the above general formulation of problem (1)−(2) can be written in the following form:

$$\max_{x \in X} \mu_C^1(x), \tag{3}$$

$$X = \left\{ x: arg\left(\max_{x \in \Omega} \mu_C^i(x) \geq \mu_R^i\right) \wedge arg\max_{x \in \Omega} \sum_{q=1}^{L} \beta_q\, \mu_q(x) \wedge \sum_{q=1}^{L} \beta_q = 1 \wedge \beta_q \geq 0, i = \overline{2,m}, q = \overline{1,L} \right\}. \tag{4}$$

In the above formulation: Ω – the domain of determining the possible values of **x**; – logical "and", requiring the truth of all expressions called through them; the $\mu_C^1(x)$ - main criterion; $\mu_C^i(x)$ – the remaining local criteria taken into account as part of the constraints; μ_R^i – boundary values for local criteria set by DMs, experts; $\mu_q(x), q = \overline{1,L}$ – membership functions evaluating the degree of fulfillment of fuzzy constraints; X – the area of acceptable solutions, i.e. $x = (x_1, \dots, x_n)$, specified by the technological regulations of the facility.

By changing the values μ_R^i and/or vectors of the weighting coefficients of constraints, it is $\beta = (\beta_1, \dots, \beta_L)$ possible to obtain a family of solutions to problem (3)−(4): $x(\mu_R^i, \beta)$. In the process of solving a multi-criteria problem in a fuzzy environment, the DMs, based on its preference, taking into account the current situation in production, market demand, iteratively selects the best of the family of solutions. To solve the above problem (3)−(4), based on the adaptation of the principal criterion and ideal point methods for fuzziness, a heuristic method can be developed that works with DMs' participation and allows iteratively improving the solutions. This method will be effective if it is possible and appropriate data are available to apply the principles of principal criterion (for criteria) and Pareto optimality (for constraints). In other situations, other optimality principles need to be modified and combined. For example, if the necessary conditions and data are available to apply the principles of relative concession (for criteria) and equality (for constraints), the multi-criteria optimisation problem in a fuzzy environment can be formulated as follows:

$$\max_{x \in X} \sum_{i=1}^{m} \gamma_i \log \mu_C^i(x), \quad (5)$$

$$X = \{x: \arg(\beta_1 \mu_1(x) = \beta_2 \mu_2(x) = \cdots = \beta_L \mu_L(x))\}. \quad (6)$$

In statement (3)‒(4): $\gamma = (\gamma_1, \dots, \gamma_m), \beta = (\beta_1, \dots, \beta_L)$ – vectors of weight coefficients, respectively, criteria and fuzzy constraints, and the remaining designations are described in the statement of the problem (1)‒(2). Then, by changing the values of the weighting coefficients of the criteria and/or constraints, it is possible to obtain a family of solutions to problem (3)‒(4): $x(\gamma, \beta)$. And the optimal solution among these solutions is chosen by the DMs based on his preference, depending on the current situation .

Now let us state the formulation of a multi-criteria optimisation problem with fuzzy constraints based on the combination and modification of the main criterion and ideal point principles:

$$\max_{x \in X} \mu_C^1(x) \quad (7)$$

$$X = \left\{x: \arg\left(\max_{x \in \Omega} \mu_C^i(x) \geq \mu_R^i\right) \arg\left(\mu_q(x) \geq \geq \min\left\|\mu_q(x) - \mu_q^{IP}\right\|_D\right), i = \overline{2,m}, q = \overline{1,L}\right\} \quad (8)$$

where $\|\cdot\|_D$ is the metric that determines the distances between the membership functions of fuzzy constraints and their ideal values. The coordinates of ideal points should be the maximum values of the degrees of fulfillment of fuzzy constraints; $\mu_q^{IP} = \max \mu_q(x), q = \overline{1,L}$. If the membership functions of fulfillment of constraints are normal, then $\mu_q^{IP} = (1, \dots, 1), q = \overline{1,L}$.

Thus, depending on the type of available information and the possibility of applying different principles of optimality, combining and modifying them, it is possible to formulate different statements of multi-criteria optimisation problems in a fuzzy environment and develop heuristic methods for their solution. This gives DMs an opportunity to choose a more effective method of solving the problem of multi-criteria optimisation in a fuzzy environment depending on the type of available information and the current situation at the production site and is the novelty of the proposed approach .

We propose a developed heuristic method for solving multi-criteria optimisation in fuzzy environment under the setting (7)–(8) based on the modification of the principal criterion (MC) and ideal point (IP) principles. The block diagram of the proposed MC+IP heuristic method is shown in Figure 2.

Here is a description of the main blocks of the developed heuristic method.

In block 2, the values of the vector of input, mode parameters, the $x = (x_1, \dots, x_n)$, priority range of $I_C = \{1, \dots, m\}$ local criteria are entered and the main criterion with priority $\mu_C^1(x)$ having priority 1 is determined.

In blocks 3 and 4 DMs define the term set describing the fuzzy constraints and for each term construct the membership functions that evaluate the degrees of fulfilment of the fuzzy constraints $\mu_q(x), q = \overline{1, L}$ and determine the boundary values for the local criteria $\mu_R^i, i = \overline{2, m}$.

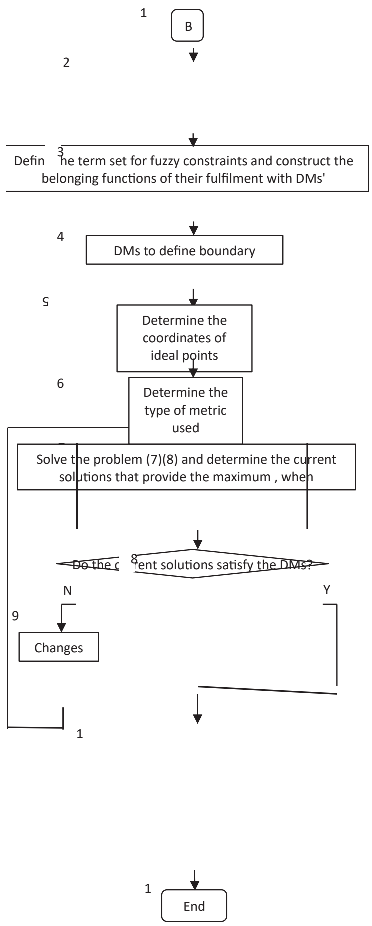


Figure 2. Block diagram of a heuristic method of multicriteria optimization in a fuzzy environment based on a combination and modification of the principles of optimality MC and IP.

The coordinates of ideal points are determined in blocks 5 and 6 according to the formula $\mu_q^{IP} = max(\mu_1(x), \dots, \mu_L(x))$. If the membership functions and fuzzy constraints are normal, then the coordinates of ideal points will be unity, i.e. $\mu_q^{IP} = (1, \dots, 1), q = \overline{1,L}$.

In block 7, the problem is solved when setting (7)–(8) and the current solutions are determined depending on the selected ones $\mu_R^i \wedge \|\cdot\|_D$. The current solutions are the values of the vector of input, mode parameters $x(\mu_R^i, \|\cdot\|_D)$, providing the maximum of the main criterio $\mu_C^1(x)$, the values of other criteria not less than their specified boundary values $\mu_C^i(x) \geq \mu_R^i$ and the maximum degrees of fulfilment of fuzzy constraints. The maximum degrees of fulfilment of the fuzzy constraints are determined by minimising the distance between them and their ideal values, i.e. $\mu_q(x) \geq min\|\mu_q(x) - \mu_q^{IP}\|_D$.

In block 8, the condition is checked whether the obtained current solutions satisfy the DMs in the previous block. If the current solutions do not satisfy the DMs, they are corrected with boundary values $\mu_R^i, i = \overline{2,m}$ and/or a different kind of metric is chosen $\|\cdot\|_D$ (block 9), and the next iteration starts back from block 6 to improve the solution.

If solutions satisfying the DMs are obtained, the transition is made to the next block 10 to derive efficient solutions. Effective solutions are those satisfying the DMs and the solutions chosen by him [Wen and Wang Hui 2018]:

– vector values $x\ (\mu_R^i, \|\cdot\|_D)$, providing the maximum of the main criterion $\mu_C^1\left(x\ (\mu_R^i, \|\cdot\|_D)\right)$;

– the local criteria values $\mu_C^i\left(x\ (\mu_R^i, \|\cdot\|_D)\right), i = \overline{2,m}$ not less than their specified boundary values μ_R^i;

– maximum values of the belonging function evaluating the degrees of fulfilment of fuzzy constraints $\mu_1\left(x\ (\mu_R^i, \|\cdot\|_D)\right), \dots, \mu_L\left(x\ (\mu_R^i, \|\cdot\|_D)\right)$. The degrees of fulfilment of fuzzy constraints are defined as the minimum distances of their belonging function from their ideal values: $\mu_q(x) \geq min\|\mu_q(x) - \mu_q^{IP}\|_D, q = \overline{1,L}$.

Results. The problem of multicriteria optimization of the delayed coking process with fuzzy constraints is solved based on a system of models of coke reactors developed in and given in appendices A-D.

We concretize the general formulation of the multicriteria optimization problem with fuzzy constraints (7)–(8) for the optimization of the delayed coking process occurring in coke reactors of DCU Atyrau refinery:

$$\max_{x \in X} \mu_C^1(x), \tag{9}$$

$$X = \left\{x: arg\left(\max_{x \in \Omega} \mu_C^2(x) \geq \mu_R^2\right) arg\left(\mu_q(x) \geq \right.\right.$$

$$\left.\left. \geq min\|\mu_q(x) - \mu_q^{IP}\|_D\right), q = 1,2\right\}, \tag{10}$$

where $\mu_C^1(x)$ – is the main criterion: the volume of coke from coking reactors; $\mu_C^2(x)$ – the local criterion: the volume of petroleum vapor from coking reactors; μ_R^2 – the boundary value of the local criterion; $\mu_q(x), q = 1,2$ – membership functions evaluating the degrees of fulfillment of fuzzy restrictions on coke quality indicators: volatility $(\mu_1(x))$ and ash content $(\mu_2(x))$; $x = (x_1, \dots, x_5)$ – the vector of input, operating parameters of coke reactors: x_1 – volume of raw materials; x_2 and x_3 – temperature and pressure of coking reactors; x_4 – coking capacity of raw materials; x_5 – recirculation coefficient.

The optimal solution of the above two-criteria optimisation problem with two fuzzy constraints is such a value of the vector of input mode parameters $x \;\; = (x_1 \;, x_2 \;, x_3 \;, x_4 \;, x_5 \;)$, in which the following is achieved:

– the maximum of the main criterion $\mu_C^1(x \;\;)$;

– the second criterion will be no less than the specified boundary value $\mu_C^2(x \;\;) \geq \mu_R^2$; the maximum values of the function are provided to fulfill two fuzzy constraints.

We present the results of solving the problem of optimizing the delayed coking process (9)–(10) based on the MC+IP heuristic method proposed in Section 2 of the DCU 21-10/6 of Atyrau refinery coking reactor model system.

1. With the involvement of DMs (senior operators of the coke reactor unit), experts, the vector of input, operating parameters affecting the coking process were determined: $x = (x_1, \dots, x_5)$, где x_1 – volume of raw materials, x_2 and x_3 – temperature and pressure of coking reactors; x_4 – coking of raw materials; x_5 – recirculation coefficient. They also introduced a number of priorities, $I_C = \{1,2\}$, where 1 is priority of the main criterion $\mu_C^1(x)$ (the volume of coke from reactors), 2 is priority of the second criterion $\mu_C^2(x)$ (the volume of vapors of petroleum products from reactors).

2. The following term-sets $T(Y)$ = {low, medium, high} are defined with DMs involvement for two fuzzy constraints on coke quality parameters: “coke volatility should be no more than $\lesssim 12\%$”; “coke ash content should be no more than $\lesssim 0.7\%$. Then, for each term, membership functions are constructed that evaluate the degrees of fulfillment of fuzzy constraints according to the exponential formula proposed by us in [17]: $\mu_q^t(x) = exp$, where q is the number of fuzzy constraints, t is the number of the term; Q_t и N_t – are the coefficients of coarse and fine tuning identified when approximating the graph of the function; y_j и y_j^m – is the fuzzy parameter and the maximum numerical value corresponding to it (where the membership function takes the maximum value). Thus, the membership functions for the volatility $\mu_1^t(x), t = \overline{1,3}$ and ash content of coke are $\mu_2^t(x), t = \overline{1,3}$ constructed in the form:

$$\mu_1^1(x) = exp$$
$$\mu_1^2(x) = exp$$
$$\mu_1^3(x) = ex$$

where Q_t=0.5), =0.3); $N_t = 0.55; 0.50; 0.45$ (for $\mu_1^t(x), t = 1,2,3$); $N_t = 0.20; 0.15; 0.10$); (for $\mu_2^t(x), t = 1,2,3$); y_j^m=7;11;14); (for $\mu_1^t(x)$, $t = 1,2,3$); y_j^m=3;5;7 (for $\mu_2^t(x), t = 1,2,3$). The fuzzy values of the volatility $\tilde{y}_3$ and ash content of $\tilde{y}_4$ coke are determined by fuzzy models that evaluate the quality of coke depending on the operating parameters of coke reactors developed by us in [34]. These models are given in Appendix C and D.

3. DMs defined the boundary values for the local criterion with priority 2 − $\mu_C^2(x)$: $\mu_R^2 = 8м^3$.

4. The coordinates of ideal points are determined by the formula $\mu_q^{IP} = max(\mu_1(x), \mu_2(x))$, since in our case the membership function is normal, units are defined as the coordinates of ideal points, i.e.: $\mu_q^{IP} = (1,1)$.

5. The type of metric used is determined, and the $\|\mu_q(x) - \mu_q^{IP}\|_D$ Euclidean metric is selected:

$$\|\mu_q(x) - \mu_q^{IP}\|_E^2 = \sum_{q=1}^{2} \sqrt{\beta_q \left(\max_{x\in\Omega} \mu_q(x) - \mu_q^{IP}\right)^2},$$

where $\beta_q, q = 1,2$ – are the weight coefficients of fuzzy constraints. Initially, they are chosen by the DMs to be equal, i.e.: $\beta_1 = 0.5; \beta_2 = 0.5$.

6. The problem has been solved (7)–(8), i.e. maximizing the main criterion (coke volume) (7) on the set of solvable solutions *X*, defined by expression (8). In this case, the values of the main and local criterion are determined on the basis of the models developed in [36], determining the volumes of coke and oil vapours depending on the $x = (x_1, \dots, x_5)$. Since the modified on the basis of the selected principles of optimality problem of multi-criteria optimization in a fuzzy environment is reduced to a single-criteria optimization problem with three constraints, the obtained problem is solved on the basis of the penalty function method using the Manager software package. The problem is solved iteratively, and current solutions are defined in each iteration:

− the value of the vector of input and mode parameters depending on the value of the boundary value of the local criterion μ_R^2 and the type of the selected metric $\|\cdot\|_D$: $x(\mu_R^2, \|\cdot\|_E^2)$;

− the value of the main criterion $\mu_C^1\left(x(\mu_R^2, \|\cdot\|_E^2)\right)$ achieved when $x(\mu_R^2, \|\cdot\|_E^2)$;

− the value of the focal criterion satisfying the condition: $\mu_c^2\left(x(\mu_R^2, \|\cdot\|_E^2)\right) \geq \mu_R^2$;

– maximum values of the accessory function, evaluating the fulfillment of fuzzy constraints $\mu_q\left(x(\mu_R^2, \|\cdot\|_E^2)\right)$ and satisfying the condition $\mu_q\left(x(\mu_R^2, \|\cdot\|_E^2)\right) \geq min\|\mu_q(x) - \mu_q^{IP}\|_D$.

7. The current solutions $x(\mu_R^2, \|\cdot\|_E^2)$ obtained at the previous point are presented to the DMs to analyse and make a final decision based on his preference, which are the best given the current production situation and market demand for the products produced. Since the current solutions obtained in the first 4 iterations did not satisfy the DMs, in order to improve the solution, he adjusted the values μ_R^2 and/or vector

of weight confidants in the metric $\beta = (\beta_1, \beta_2)$ and the transition was carried out back to point 6. At 5-titeration, the best results satisfying the DMs are obtained and the transition is made to the next point 8.

8. The best solutions are derived, chosen by DMs $(\mu_R^2, \|\cdot\|_E^2)$,: which provide the maximum value of the main criterion $\mu_C^1\left(x \quad (\mu_R^2, \|\cdot\|_E^2)\right)$, satisfying the given boundary values of the second criterion: $\mu_C^2\left(x \quad (\mu_R^2, \|\cdot\|_E^2)\right) \geq \mu_R^2$ and the maximum degrees of fulfilment of the fuzzy constraints $\mu_q\left(x \quad (\mu_R^2, \|\cdot\|_E^2)\right), q = 1,2,$ which are determined from the minimisation condition of the chosen metric. The final results are listed in table 1.

Table 1. The results of optimization of the process of delayed coking of DCU 21-10/6 of Atyrau refinery by the well-known deterministic method and the proposed heuristic method MC+IP and their comparison with real data obtained by DMs on DCU 21-10/6 of Atyrau refinery.

Criteria and fuzzy constraints	**A well-known method**	***MC+IP* heuristic method**	**Real data**
Coke volume, t/h, 1 is the main criterion $\mu_C^1\left(x \quad (\mu_R^2, \|\cdot\|_E^2)\right)$;	21,3	23,9	23,2
The volume of vapors of petroleum products, t/h, 2-local criterion $\mu_C^2\left(x \quad (\mu_R^2, \|\cdot\|_E^2)\right)$;	8,5	8,5	8,5
Membership functions that evaluate the extent to which fuzzy constraints are fulfilled: "Coke volatility $\lesssim 12\%$" $-\mu_1\left(x \quad (\mu_R^2, \|\cdot\|_E^2)\right)$;	–	1.0 [11]	$(12)^L$
"The ash content of coke is $\lesssim$ 0.7% by weight.": – $\mu_2\left(x \quad (\mu_R^2, \|\cdot\|_E^2)\right)$;	–	1.0 [0.65]	$(0.7)^L$
Optimal parameters of coking rectors: x_1 – the volume of raw materials (tar); t;	105	105	105
x_2 – temperature of coking reactors, °C;	489	487	488
x_3 –pressure of coking reactors, kg/cm²;	5,0	5,0	5,0
x_4 –coking properties of raw materials, %;	7	7	7
x_5 –recirculation coefficient.	11	11	11

Note: – means that these parameters are not determined by this method; $()^L$ – these parameters are not directly measured, evaluated in a laboratory with human participation; the final values $\mu_R^2 = 8.5$; and $\beta = (0.70, 0.30)$.

Discussions. The formulation of the problem of optimisation of delayed coking process in fuzzy environment (9)−(10) is a two-criteria problem and with two fuzzy constraints. Coke volume is considered as the first, i.e. the main criterion, and the second − is the volume of petroleum product vapours from coke reactors. When solving the formulated problem, the main criterion is $\mu_C^1(x)$ maximized, and the second, local criterion is taken into account as part of the constraints, taking into account the boundary value imposed on it μ_R^2. At the same time, the conditions of fuzzy constraints shall be met. The fuzzy constraints in the problem to be solved are the requirements to the qualitative indicators of coke, i.e. its volatility and ash content, which are set as fuzzy instructions 'not more than' according to the standard. The values of criteria and constraints depend on the vector of input, mode parameters of coke reactors. These independent values are defined in the form of coke reactor models developed by us in, which are used in this paper to optimise the delayed coking process occurring in coke reactors.

The two-criteria optimisation problem with fuzzy constraints is solved by the proposed heuristic method using DM's experience, knowledge and intuition. When solving the problem sequentially from iteration to iteration, the results are improved until satisfying DMs, the best solutions are obtained. Comparing and discussing the obtained optimisation results of the proposed MC+IP heuristic method and the known deterministic method given in Table 1, the following advantages of the proposed heuristic method can be pointed out:

1. Unlike the known approaches to solving fuzzy problems, the proposed heuristic MC+IP method allows solving the problem of multi-criteria optimization in a fuzzy environment without converting it to a set of clear problems. Since the transformation of a fuzzy problem to a set of crisp problems loses some of the collected fuzzy information, the adequacy of the obtained solutions is reduced. The proposed heuristic method due to the maximum use of the collected fuzzy information allows to obtain highly adequate solutions of the optimisation problem in a fuzzy environment. This is confirmed by the data in Table 1, showing a more accurate match of the results obtained by the heuristic method to real, experimental data, compared to the deterministic method.

2. The developed heuristic method based on the MC and IP optimality principles in contrast to the known methods allows to determine the values of the belonging function of fuzzy constraints, i.e. the degrees of their fulfilment. This allows us to efficiently solve the optimisation problem with fuzzy constraints by considering the degrees of their fulfilment.

3. The proposed approach to the development of a heuristic method for solving multicriteria optimisation problems in a fuzzy environment allows us to develop other heuristic methods based on the modification and combination of other optimality principles, such as maximin, equality, relative concession and others. This allows DMs to choose a more effective method for solving multi-criteria optimisation problems in a fuzzy environment depending on the type of available information and the current situation in production and on the market of manufactured products.

The results of the two-criteria optimisation with fuzzy constraints presented in Table 1 show that the proposed heuristic method provides better results compared to the known deterministic method. As can be seen from the comparison results in Table 1, the proposed heuristic method MC+IP allows to improve the values of criteria: the volume of whole product, i.e. coke by 2.6 tonnes per 1 hour or 12.21%, compared to the known method. At the same time, the proposed heuristic method allows to estimate the degree of fulfilment of the requirements of fuzzy constraints $\mu_1\left(x \quad (\mu_R^2, \|\cdot\|_E^2)\right), \mu_2\left(x \quad (\mu_R^2, \|\cdot\|_E^2)\right)$, which is not determined by known methods.

Conclusion. A heuristic approach to solving multi-criteria fuzzy optimisation is proposed to make maximum use of the experience, knowledge and intuition of DMs and experts. A heuristic method of multi-criteria optimisation with fuzzy constraints is developed by combining and modifying the principles of optimality of the main criterion and ideal point. The proposed method is implemented in solving the two-criteria optimisation problem of delayed coking process of DCU Atyrau refinery with two fuzzy constraints.

The main results obtained in the research process and conclusions are:

1) The formulation of a multi-criteria fuzzy optimisation problem based on the combination and modification of various optimality principles to work in a fuzzy environment is formalised and presented;

1) A heuristic method based on the combination and modification of the principal criterion and ideal point principles is developed to work in fuzzy environment;

3) On the basis of coking reactor models and the proposed heuristic method MC+IP the problem of two-criteria optimisation of delayed coking process with fuzzy constraints is solved.

The developed heuristic method for solving a multi-criteria optimisation problem in a fuzzy environment makes it possible to use DMs' and computational capabilities to iteratively improve and identify efficient solutions taking into account DMs' preference.

The novelty of the proposed heuristic approach to solving a multi-criteria optimisation problem in a fuzzy environment is to solve such a problem in a fuzzy environment maximally using fuzzy information, i.e. knowledge, experience and intuition of the DMs. This approach allows to obtain more effective and adequate solutions to the problem of optimisation of operating modes of production facilities characterised by fuzziness.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the corresponding author.

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