ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

ҚАЗАҚСТАН РЕСПУБЛИКАСЫ
ҰЛТТЫҚ ҒЫЛЫМ АКАДЕМИЯСЫ
Satbayev University

ХАБАРЛАРЫ

ИЗВЕСТИЯ

НАЦИОНАЛЬНОЙ АКАДЕМИИ
НАУК РЕСПУБЛИКИ
КАЗАХСТАН
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N E W S

OF THE ACADEMY OF SCIENCES
OF THE REPUBLIC OF
KAZAKHSTAN
Satbayev University

SERIES

OF GEOLOGY AND TECHNICAL SCIENCES

4 (454)

JULY – AUGUST 2022

THE JOURNAL WAS FOUNDED IN 1940

PUBLISHED 6 TIMES A YEAR

ALMATY, NAS RK

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«ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Меншіктеуші: «Қазақстан Республикасының Ұлттық ғылым академиясы» РҚБ (Алматы қ.).

Қазақстан Республикасының Ақпарат және қоғамдық даму министрлігінің Ақпарат комитетінде 29.07.2020 ж. берілген **№ KZ39VPY00025420** мерзімдік басылым тіркеуіне қойылу туралы куәлік.

Тақырыптық бағыты: *геология, мұнай және газды өңдеудің химиялық технологиялары, мұнай химиясы, металдарды алу және олардың қосындыларының технологиясы.*

Мерзімділігі: жылына 6 рет.

Тиражы: 300 дана.

Редакцияның мекен-жайы: 050010, Алматы қ., Шевченко көш., 28, 219 бөл., тел.: 272-13-19

http://www.geolog-technical.kz/index.php/en/

Типографияның мекен-жайы: «Аруна» ЖК, Алматы қ., Мұратбаев көш., 75.

«Известия НАН РК. Серия геологии и технических наук».
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Собственник: Республиканское общественное объединение «Национальная академия наук Республики Казахстан» (г. Алматы).

Свидетельство о постановке на учет периодического печатного издания в Комитете информации Министерства информации и общественного развития Республики Казахстан **№ KZ39VPY00025420,** выданное 29.07.2020 г.

Тематическая направленность: *геология, химические технологии переработки нефти и газа, нефтехимия, технологии извлечения металлов и их соеденений.*

Периодичность: 6 раз в год.

Тираж: 300 экземпляров.

Адрес редакции: 050010, г. Алматы, ул. Шевченко, 28, оф. 219, тел.: 272-13-19

http://www.geolog-technical.kz/index.php/en/

Адрес типографии: ИП «Аруна», г. Алматы, ул. Муратбаева, 75.

News of the National Academy of Sciences of the Republic of Kazakhstan. Series of geology and technology sciences.
ISSN 2518-170X (Online),
ISSN 2224-5278 (Print)

Owner: RPA «National Academy of Sciences of the Republic of Kazakhstan» (Almaty).

The certificate of registration of a periodical printed publication in the Committee of information of the Ministry of Information and Social Development of the Republic of Kazakhstan **No. KZ39VPY00025420,** issued 29.07.2020.

Thematic scope: *geology, chemical technologies for oil and gas processing, petrochemistry, technologies for extracting metals and their connections.*

Periodicity: 6 times a year.

Circulation: 300 copies.

Editorial address: 28, Shevchenko str., of. 219, Almaty, 050010, tel. 272-13-19

http://www.geolog-technical.kz/index.php/en/

Address of printing house: ST «Aruna», 75, Muratbayev str, Almaty.

NEWS *of the National Academy of Sciences of the Republic of Kazakhstan*
SERIES OF GEOLOGY AND TECHNICAL SCIENCES
ISSN 2224-5278
Volume 4, Number 454 (2022), 152-170
https://doi.org/10.32014/2022.2518-170X.207

UDC 519.81: 629.359

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METHOD OF DEVELOPING MODELS OF CHEMICAL AND TECHNOLOGICAL SYSTEMS OF OIL REFINING UNDER UNCERTAINTY

Abstract. At present, many complex technological systems of oil refining and other industries are characterized by uncertainty due to the probabilistic and fuzzy nature of the initial information, which creates problems in developing their mathematical models and optimizing their operating modes**.** In this regard, the development of models and optimization of their modes of operation of such systems is an urgent scientific and technical problem. This paper proposes and a new and effective approach to the development of a system of mathematical models and the modelling of processes for oil refining, which uses various types of data, for use in conditions of uncertainty brought about by the random nature and fuzziness of input data. The idea and originality of the proposed method lye in the fact that, from the beginning, according to the research results for each unit, and based on the data which has been gathered and the selection criteria, a model is constructed for each unit. Then, in order to model the process as a whole, the models which have been developed are combined to form an integrated system. The method which has been developed has been successfully implemented in the construction of a system of models for the main units of the catalytic reforming installation LG-35-11/300-95 at the Atyrau Refinery. A comparison of existing results, with the results of modelling using the proposed method, and also with experimental data from the LG installation at the Atyrau Oil Refinery shows the effectiveness and advantages of the proposed approach to modelling for complex

inter-dependent technological processes. The structure for a system of computer modelling and optimisation for working regimes for technological processes in the oil industry based on the mathematical modelling of their functioning has been proposed.

Key words: Mathematical modelling, computer modelling and optimisation, technological facilities of the oil industry, reforming plant, theory of fuzzy sets, membership function, (DM) - decision maker.

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АНЫҚСЫЗДЫҚ ЖАҒДАЙЫНДА МҰНАЙ ӨҢДЕУ ХИМИЯЛЫҚ-ТЕХНОЛОГИЯЛЫҚ ЖҮЙЕЛЕРІНІҢ МОДЕЛЬДЕРІН ҚҰРУ

Аннотация. Қазіргі уақытта мұнай өңдеу және басқа да салалардың көптеген күрделі технологиялық жүйелері бастапқы ақпараттың кездейсоқтығы мен айқынсыздығы сипатына байланысты анықсыздықпен сипатталады, бұл жағдай олардың математикалық модельдерін құруда және жұмыс режимдерін оптимизациялауда проблемалар тудырады. Осыған байланысты мұндай жүйелердің модельдерін құру және олардың жұмыс режимдерін оптимизациялау өзекті ғылыми-техникалық мәселе болып есептеледі. Бұл жұмыста кездейсоқтық және айқынсыздыққа байланысты туындайтын анықсыздық жағдайында түрлі деректер мен ақпараттарды пайдалану арқылы мұнай өңдеу технологиялық жүйелерінің математикалық модельдер жүйесін құру және модельдеу үшін тиімді тәсіл ұсынылады. Ұсынылатын тәсілдің идеясы мен ерекшелігі мынада: технологиялық жүйенің әрбір агрегатына зерттеу нәтижелеріне сәйкес және жинақталған ақпараттар мен таңдау критерийлеріне сүйене отырып, әр агорегатқа құрылуы мүмкін және тиімді модель құрылады. Содан кейін жүйеде өтетін технологиялық процесті тұтастай модельдеу үшін құрылған модельдер бір жүйеге (модельдер пакетіне) біріктіріледі. Жасақталған тәсіл Атырау мұнай өңдеу зауытында ЛГ-35-11/300-95 каталитикалық риформинг қондырғысының негізгі агрегаттарының модельдер жүйесін құруда сәтті қолданылған. Белгілі модельдеу нәтижелері мен ұсынылған модельдеу тәсілі нәтижелерін, сондай-ақ Атырау мұнай өңдеу зауытындағы ЛГ каталитикалық риформинг қондырғысының тәжірибелік деректерімен салыстыру күрделі өзара байланысқан агорегаттардан тұратын технологиялық жүйелерді модельдеуге ұсынылған тәсілдің тиімділігі мен артықшылықтарын көрсетеді. Құрылған модельдер негізінде мұнай өнеркәсібіндегі технологиялық жүйелердің жұмыс режимдерін компьютерлік модельдеу және оптимизациялау жүйесінің құрылымы ұсынылды.

Түйін сөздер: Математикалық модельдеу, компьютерлік модельдеу және оптимизациялау, мұнай өнеркәсібі технологиялық нысандары, риформинг қондырғысы, айқын емес жиындар теориясы, тиітілік функциясы, (ШҚТ) – шешім қабылдайтын тұлға.

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МЕТОД РАЗРАБОТКИ МОДЕЛЕЙ ХИМИКО-ТЕХНОЛОГИЧЕСКИХ СИСТЕМ НЕФТЕПЕРЕРАБОТКИ В УСЛОВИЯХ НЕОПРЕДЕЛЕННОСТИ

Аннотация. В настоящие время многие сложные технологические системы нефтепереработки и других отраслей характеризуются неопределенностью из-за вероятностного и нечеткого характера исходной информации, что создает проблемы разработки их математических моделей и оптимизации их режимов работы. В этой связи разработка моделей и оптимизации их режимов работы таких систем является актуальной научно-технической проблемой. В данной работе предлагается эффективный подход к созданию и моделированию системы математических моделей технологических систем нефтепереработки с использованием различных данных и информации в случаях неопределенности и случайности. Идея и особенность предлагаемого подхода заключается в том, что сначала для каждого агрегата технологической системы разрабатывается возможная и эффективная модель по результатам исследования и на основе собранной информации и критериев выбора. Затем созданные модели объединяются в одну систему (пакет моделей) для моделирования технологического процесса, протекающего в системе агрегатов. Разработанный подход был успешно применен при создании системы моделей основных агрегатов установки каталитического риформинга ЛГ-35-11/300-95 Атырауского нефтеперерабатывающего завода. Сравнение известных результатов моделирования и результатов предлагаемого подхода к моделированию, а также с экспериментальными данными установки каталитического риформинга ЛГ на Атырауском НПЗ показывает эффективность и преимущества предлагаемого подхода для моделирования сложных технологических систем, состоящих из взаимосвязанных агрегатов. На основе созданных моделей предложена структура системы компьютерного моделирования и оптимизации режимов работы технологических систем нефтяной отрасли.

Ключевые слова: математическое моделирование, компьютерное моделирование и оптимизация, технологические объекты нефтяной промышленности, установка риформинга, теория нечетких множеств, функция принадлежности, ЛПР – лицо, принимающее решение.

Introduction. Some of the main problems in the development of production are related to the intensification of production and the raising of the quality and efficiency of technological and industrial processes. One of the most promising ways of solving these problems involves the raising of the efficiency of the control of industrial installations, based on the use of scientifically based methods for the working out of and taking decisions using appropriate mathematical tools and computer technology. Such problems, related to the raising of the efficiency and quality of the working of technological processes are actively discussed in scientific and technical literature (Tanirbergenova et all., 2021: 242 – 258, Nguyen et al., 2021:26). There is a current series of papers on methods for mathematical modelling and control of technological processes in the oil refining industry (Dmitrievsky et all., 2018:136-145., Orazbayev et all., 2020: 1235-1241). However, there is a class of objects, various industrial situations and their control tasks, the formalisation and solution of which, within the limits of traditional approaches, cannot be obtained or do not give meaningful results. Such objects and tasks may include production systems functioning in conditions of uncertainty connected to the randomness and fuzziness of input data, and the problems of the formalisation and solution of the task of modelling and optimisation of their working regimes for various industrial situations. In addition to the fuzziness of input data, the solution of these tasks is complicated by the complexity and multi-criterial nature of the objects being controlled (Orazbayev et all., 2021: 498-507., Orazbayev et all., 2020: 4736).

In connection with the complexity or impossibility of measuring a range of parameters and indicators, many technological and industrial processes are difficult to describe quantitatively, which hinders the use of deterministic mathematical methods for the modelling and optimisation of their working regimes. This has led to the appearance of new methods for the formalisation and solution of the tasks in question, which rely on fuzzy data provided by the person making the decision (the Decision Maker, DM) and experts and specialists in the form of their understanding of the functioning of the object, taking into account their preference in the decision-making process (Orazbayev et all., 2021:147–182).

The successful solution of the problem of modelling and the task of multi-criterial optimisation, which arises in the control of industrial objects in conditions of uncertainty and fuzzy input data, requires the development of a methodology for the construction of mathematical models for technological objects in these conditions and the development and further improvement of a method for the formalisation and solution of the task of their modelling and optimisation in a fuzzy environment, together with the development of algorithms and programmes to implement these methods using modern computer technology. Such problems are the subject of research in this paper.

Oil refining is essentially the totality of the physical and physio-chemical processes, including processes to prepare the crude oil for refining as well as primary and deep refining of oil and oil products (Zhumadillayeva et all., 2020:11) which takes place in oil refineries. Various technological processes in the oil refining industry are carried out in custom-built assemblies. In industrial conditions the end products from the process are usually obtained in a set of such technological assemblies (installations), which include various inter-dependent assemblies, for example heaters, reactors, rectification columns, heat-exchangers and others.

Questions relating to the efficient control of technological processes for oil refining, and their optimisation according to economic and ecological criteria using mathematical modelling, have generated a lot of interest in recent times. In this connection, much research has been started aimed at resolving these issues (Orazbayev et all.,2021:147-182., Yang et all., 2022:988., Sansyzbay et all.,2019:1124).

For effective research and the optimisation of processes and the units used in oil refining, it is necessary to construct for them mathematical models which take into account the nature and state of the process, its type, and other peculiarities of the object. Since technological installations in the oil refining industry are made up of a complex set of inter-dependent assemblies, it becomes necessary to develop a package, ie a system of models, which allow for system simulation of the object to be carried out. Furthermore, issues of multi-criteriality and uncertainty often arise in industrial installations for oil refining, and these make it harder to construct the necessary mathematical models and optimisation algorithms.

Issues relating to the development of a package of inter-dependent models (system simulation) for complex technological installations, such as are required for oil refining, and methods for the optimisation of their working regimes in conditions of multi-criteriality and uncertainty caused by the fuzzy nature of input data, are some of the least researched problems in scientific research and literature and remain and not fully resolved. In this connection, the development of effective methods for the mathematical modelling of technological objects and processes in the oil refining industry in a real-life environment which is often characterised by uncertainty, using computer technological, is one of the most pressing scientific and practical issues in the field of oil refining.

A formal mathematical description includes the totality of the dependencies by which the various parameters of the object and process are related in one integrated system of equations (Orazbayev et all.,2019:1124). These relationships may include formulae reflecting general physical laws (for example the laws of mass and energy) and equations describing elementary processes (for example reciprocity or physio-chemical transformations). Furthermore, the mathematical description also includes various empirical and semi-empirical dependencies between the various object parameters, the theoretical form of which is unknown or exceedingly complex, and also fuzzy dependencies and formulae which have been derived from the knowledge and experience of specialists and experts in the form of logical rules for a provisional conclusion.

It is generally accepted that, in order to model complex technological processes in conditions of uncertainty resulting from the stochastic nature of the process, a method based on probability theory and mathematical statistics is used (Orazbayev et all., 2019:653-664). However, the uncertainty may be caused by the fuzzy nature of available input data, and in such cases the uncertainties do not always behave according to the assumptions of probability theory, that is the use of probabilistic methods is not justified. Furthermore, even if it is possible to describe the processes and systems using probabilistic methods, due to the lack of, complexity of and economic non-viability of gathering reliability statistical data, it becomes necessary to describe and construct non-statistical, for example fuzzy models of actual installations and processes. In this regard, one of the most promising approaches is the use of methods based on fuzzy set theory.

In order to provide for the high-quality analysis of actual technological installations and systems, approaches are required, for which a high level of accuracy and strict mathematical formalism are not absolutely necessary. The problem of uncertainty due to fuzzy input data can be solved in the investigation and modelling of complex technological objects by using fuzzy mathematical tools. In such a way, it then becomes necessary to develop a generalised method for the construction of mathematical modelling and the modelling of complex technological objects which are functioning in various types of conditions of uncertainty.

Research materials and methods. Technological installations in the oil refining industry consist of several inter-dependent technological assemblies. For that reason, for research into the maintenance of a technological process in an effective regime, it is necessary to have related mathematical models of the assemblies, which have been constructed using a systems approach. These models should allow for the forecasting of the influence of the assembly parameters on the processes taking place within them, on the transient and end products and on the working of the installation as a whole. In order to draw up a mathematical description of the relationship of the parameters of the object in which we are interested, usually the combination of various types of data is used:

- theoretical understanding of the nature and character of the process taking place in the object;
- bench mark statistical data, characterising the functioning of the system being analysed;
- data from expert evaluations, including fuzzy data, qualitatively describing the state of the object.

The main approaches to the construction of mathematical models for technological objects and processes are: theoretical, experimental-statistical, an approach based on a fuzzy set theory method and a combined approach.

We are considering the main types of mathematical models obtained on the basis of the above-mentioned approaches and used in the analysis and control of technological systems for industrial installations.

Deterministic Models for technological assemblies and processes are developed on the basis of abstract models of the structure of the system being described and the regularity of the behaviour of its individual sub-systems, that is, these models are constructed based on a theoretical approach, using equations describing each of the processes which takes place in the given type of object.

In industrial conditions, when a large number of parameters simultaneously influence the state of the technological units, random effects play an important role. In order to describe such assemblies, we can consider any actual process which has intrinsic random fluctuations, for example, caused by the physical instability of any factors $x_i(\tau)$ or external random variations. Thereby, in the case of an even mean value of the input characteristic $x(\tau)$ at the instants τ_1 and τ_2 the output parameters $\zeta_i(\tau)$ will be distinct, therefore, for such stochastic (probabilistic) processes, where random fluctuations of $\Delta x_i(\tau)$ in comparison with $x_i(\tau)$ and random external variations $\zeta_i(\tau)$ must not be ignored, it is necessary to characterise the system taking into account statistical laws for the assignment of instantaneous values $y(\tau)$ relative to the average value $y_{av}(\tau)$ of the equation:

$$y(\tau) = y_{av}(\tau) + \Delta y(\tau) = f(y_{av}) + \xi(\Delta x, \xi) \qquad (1)$$

Models of type (1), reflecting the random nature of the object's parameters and other factors, are known as stochastic (Orazbayev et all., 2019:182-194) models. As the value of parameters Δx and ξ in equation (1) are reduced, the structure of the equation continuously approaches that of the equation $y = f(x)$, which describes a deterministic system. In other words, statistical models are a broader class of models and include deterministic models as an extreme special case, for which the output variables y are unequivocally determined by input variables x.

One of the most promising approaches to the surmounting of this problem, which substantially raises the effectiveness of methods for mathematical modelling and control of technological objects in oil refining which are complex and difficult to describe quantitatively, is based on the use and formulation of a priori qualitative data relating to the peculiarities of the functioning of the objects in question. The effective formulation of qualitative data involves knowledge and the opinion of experts and specialists about the object being studied, and may be implemented based on methods using fuzzy set theory and mathematical tools which are described in research papers (Toloo et all., 2022:1796).

We are considering here technological objects for which the construction of mathematical models is hindered, on the one hand, by a high level of a priori uncertainty and lack of data relating to its processes, and on the other hand by the fact that input and output variables are, by nature, diffuse and fuzzy. However, a person, an operator, is able to control them, based on several models of a qualitative character, formulated according to his knowledge acquired in the process of study and observance of the functioning of the object in question. It is possible to obtain a formalised model for such an assembly without having to recourse to the use of complex mathematical structures, based on the ability of the person to express its essence in fuzzy terms using natural language. The simplest model of this type can be expressed as "*if* $\tilde{x}_i$ is given at the system input, then at its output we get $\tilde{y}_j$", where $\tilde{x}_i$ and $\tilde{y}_j$ are terms from the term set T(X,Y). Further, using fuzzy set theory methods to process the qualitative data which has been obtained, we derive a quantitative value or model for the object, for use in its optimisation and control.

In this way, using mathematical tools based on fuzzy set theory, we are able to construct simpler and more effective models and algorithms for optimisation to use in the control of technological installations in conditions of uncertainty, when the use of traditional approaches is not justified or not possible.

Results. Using the results of research into the construction of mathematical models for complex objects and based on the methodology of fuzzy set theory and methods of expert evaluation, the following general method for the development of mathematical models and modelling for technological installations in the oil refining industry using various types of data (theoretical, statistical, fuzzy) is proposed. The general method, which has been developed, for the construction of mathematical models for technological installations in conditions of uncertainty based on the use of various types of data is made up of the following main steps:

1. Study of the technological system which is made up of inter-dependent units, determination of the objective of the modelling;

2. Determining the criteria for evaluation and comparison of the models which can be constructed for process elements, taking into account the objective of the modelling;

3. Expert evaluation of possible models for each unit of the industrial installation, according to the chosen criteria, and selection of the optimal type of model for each unit according to the sum of the criteria;

3.1. If the theoretical data for the description of the working of any particular unit is sufficient and according to the sum of the criteria a deterministic model is found to be efficient, then deterministic models are constructed for the unit in question, based on analytical techniques;

3.2. If the statistical data for the description of the working of a particular unit is sufficient or the gathering of such data is possible, and at the same time according to the sum of the evaluation criteria and comparison, a statistical the model is found to be efficient, then statistical models are constructed for that unit, based on experimental and statistical methods;

3.3. If the theoretical and statistical data is not sufficient to describe the working of any particular unit and the gathering of such data is not practicable, but the gathering of fuzzy data describing the working of the unit and its processes is possible, and also according to the sum of the evaluation criteria and comparison the fuzzy model is efficient, then, fuzzy models are constructed for the unit in question, based on the fuzzy set theory method. To do so continue to step 4;

3.4. If theoretical and statistical data and fuzzy expert data is not sufficient to describe the working of any particular unit and it is not practicable to gather such data, then combined models are constructed for the unit in question, based on the combination of various types of data which has been gathered (theoretical, statistical, fuzzy). For a description of the various parameters of a particular unit, depending on the type of data, proceed to step 3.1-3.3 or 4;

4. Determination and selection of the fuzzy input $\widetilde{x}_i \in \widetilde{A}_i, i = \overline{1,n}$ and output $\widetilde{y}_j \in \widetilde{B}_j, j = \overline{1,m}$ parameters required for the construction of the model. $\widetilde{A}_i \in X, \widetilde{B}_j \in Y$ – fuzzy subsets, X,Y – universal sets. Input parameters may be non-fuzzy (deterministic) i.e., $x_i \in X_i, i = \overline{1,n}$;

5. If $x_i \in X_i$ i.e. the input parameters for the unit are deterministic (non-fuzzy), then structures are determined by fuzzy multi-regression equations $\widetilde{y}_j = f_j(x_1,...,x_n,\widetilde{a}_0,\widetilde{a}_1,...,\widetilde{a}_n)$, $j = \overline{1,m}$ (using diffraction analysis identification to solve the equations);

6. Data is gathered to describe the object being investigated based on the expert evaluations and the term-sets for the fuzzy parameters T($\widetilde{X}_i, \widetilde{Y}_j$) are determined;

7. The membership function for the fuzzy parameters $\mu_{A_i}(\widetilde{x}_i), \mu_{B_1}(\widetilde{y}_j)$ is constructed;

8. If the input and output parameters of the unit are fuzzy, then a fuzzy function, R_{ij} is formalised, which determines the relationship between $\widetilde{x}_i$ and $\widetilde{y}_j$, i.e. a linguistic model is constructed. In which case proceed to step 10;

9. If the conditions of step 5 are fulfilled, then the value of the fuzzy coefficients ($\widetilde{a}_0, \widetilde{a}_1, \ldots, \widetilde{a}_n$) identified in step 5 of the model, $\widetilde{y}_j$ are determined (parametric identification is used to solve the equation). In which case proceed to step 11;

10. If the conditions of step 8 are fulfilled, then the fuzzy values of the unit parameters are determined based on the principle of composite output, and their numerical values are determined from among many fuzzy solutions;

11. The adequacy of the model is checked. If the adequacy criteria are fulfilled, then the models which have been developed are recommended for investigation and the determination of optimal working regimes for the technological processes. Otherwise, the reason for the inadequacy is ascertained, and it is necessary to return to the corresponding step in order to resolve the issue and ensure the adequacy of the model.

We would also like to give some clarification of the steps in the method proposed above for the construction of mathematical models of systems processes in conditions of uncertainty.

In the 3rd step, the model is evaluated according to the chosen criteria by expert evaluation of each possible type of model for each unit of the technological system and taking into account the results of the evaluation (for example by means of summing the grades which have been awarded, expert evaluation), for each unit of the system, the type of mathematical model which is the most effective for the unit in question is determined. The results from this step have been laid out clearly in a table. (see Table 1). Sub-steps 3.1 and 3.2 of step 3 are carried out based on known methods for the development of deterministic and statistical models. Sub-step 3.3 is carried out based on methods for the construction of fuzzy models using methodology from fuzzy set theory and methods of expert evaluation. In the implementation of sub-step 3.4 the combination of various types of data (theoretical, statistical, fuzzy) is used and combined models are constructed.

In step 4, depending on the required accuracy of the models being developed, linguistic, fuzzy parameters (variables) are selected, which describe the qualitative functioning of the object being modelled. For convenience, the variation ranges for the fuzzy descriptive parameters are given in the form of intervals, showing the minimum($x^{\min}$, $y^{\min}$)andmaximum($x^{\max}$, $y^{\max}$)values.Theseintervals,depending on the opinion of specialists and experts, are subdivided into several sampling intervals (quanta): $x_j^{\min} = x_j^1 < x_j^2 < ... < x_j^n = x_j^{max}$, $y_j^{\min} = y_j^1 < y_j^2 < ... < y_i^n = y_j^{max}$.

In order to determine the structure of the fuzzy multiple regression equations (step 5) an approach based on fuzzy regressional analysis can be used. In this step, the determining factor is a qualitative analysis of the object, as a result of which the main parameters which influence the functioning of the system and their inter-dependencies are obtained, and a method for the identification of the model structure is determined. In general, fuzzy models are constructed in the form of fuzzy multiple regression equations.

In step 8, in order to construct a linguistic model for the object, we can use logical rules for a conditional output. The linguistic model for the object is constructed according to the results of the processed expert data. For convenience it can be formulated in the form of a table, where the various values of input parameters $\tilde{x}_i$ and the possible values of the output parameters $\tilde{y}_j$ accordingly, are shown verbally (in fuzzy form). The table should be completed with the use of the term sets, chosen in step 4. Based on the model obtained in this way, the fuzzy expression R_{ij}, which determines the relationship between, and input and output parameters is formulated.

Fuzzy expressions for the quantum p can be determined in the following way: $R_{ij}^p = A_i^p \circ B_j^p$. For the convenient assessment of the fuzzy expression R_{ij}. in calculations, it is necessary to construct a matrix of fuzzy relationship $\mu_{R_{ij}}(\tilde{x}_i, \tilde{y}_j)$, for example, in general for the sampling intervals (quanta): $\mu_{R_{ij}}^p(\tilde{x}_i, \tilde{y}_j) = \min\left[\mu_{A_i}^p(\tilde{x}_i)\mu_{B_j}^p(\tilde{y}_j), i = \overline{1,n}, j = \overline{1,m}\right]$.

In order to determine the evaluation of the parameters of the function chosen in step 5, in step 9 it is possible to use the minimisation criterion for the deviation of the fuzzy value of output parameter $\tilde{y}_j^{м}$, which has been obtained using the model, from its selected fuzzy value, obtained on the basis of expert evaluation $\tilde{y}_j^{э}$, i.e.: $R_j = \min \sum_{l=1}^{L} \left(\tilde{y}_{jl}^{м} - y_{jl}^{э}\right)^2$.

In this step, the main issue is that of selection of the means of evaluation of the unknown parameters which provide for the necessary behaviour of the object being studied. In so doing, fuzzy models are represented as fuzzy multiple regression equations:

$$\tilde{y}_j = \tilde{a}_{0j} + \sum_{i=1}^{n} \tilde{a}_{ij} x_{ij} + \sum_{i=1}^{n} \sum_{k=i}^{n} \tilde{a}_{ikj} x_{ij} x_{kj}, \; j = \overline{1,m}$$

Step 10 of the proposed method for the construction of mathematical models for technological processes in conditions of uncertainty involves the application of the compositional inference rule: $B_j = A_i \circ R_{ij}$.

With the help of this rule, it is possible to calculate the output variables, for example, based on maximising production:

$$\mu_{B_i}^{p}(\tilde{y}_j^*) = \max_{x_i \in X_i} \{\min[\; \mu_{A_i}^{p}(\tilde{x}_i^*),\; \mu_{R_{ij}}^{p}((\tilde{x}_i^*, \tilde{y}_j)]\}. \tag{2}$$

If $\tilde{x}_i$ is the measure (expert evaluation) of the values of input variables, then the desired set which belongs to the current measured value of the input variables is determined as a set, for which the measured values have the highest (maximum) degree of membership: $\mu_{A_i}(\tilde{x}_i) = \max \mu_{A_i}(\tilde{x}_i)$.

The expected values of the output variables (fuzzy values) are determined in the form of the appropriate membership function $\mu_{B_j}^{p}(\tilde{y}_j)$ (2).

Results of the Practical Implementation of the Proposed Method and their Discussion. Mathematical models for the reactors P-2, P-3, P-4,4a of the reforming unit of the installation have been constructed using statistical data and expert information which has been processed using fuzzy set theory methods, and also using material and heat balance equations.

As a result of the gathering and processing of experimental-statistical and expert data, and at the same time using the idea of the progressive inclusion of regressors (Yang et all., 2022:988) based on the method for the construction of mathematical models for technological objects in conditions of uncertainty proposed above, the structural identification of models for the reactors of the reforming installation has been carried out, in the form of multiple regression system equations (4)–(7) and a system of multiple regression fuzzy equations (8):

$$y_{R2} = a_0 + \sum_{i=1}^{5} a_i x_i + \sum_{i=1}^{5} \sum_{k=i}^{5} a_{ik} x_i x_k, \tag{3}$$

$$y_{R3} = a_0 + \sum_{i=1}^{5} a_i x_i + \sum_{i=1}^{5} \sum_{k=i}^{5} a_{ik} x_i x_k, \tag{4}$$

$$y_{R4,4a} = a_0 + \sum_{i=1}^{5} a_i x_i + \sum_{i=1}^{5} \sum_{k=i}^{5} a_{ik} x_i x_k, \tag{5}$$

$$y_j = a_{0j} + \sum_{i=1}^{5} a_{ij} x_{ij} + \sum_{i=1}^{5} \sum_{k=i}^{5} a_{ikj} x_{ij} x_{kj}, \ j = 1{,}2 \qquad (6)$$

$$\widetilde{y}_j = \widetilde{a}_{0j} + \sum_{i=1}^{5} \widetilde{a}_{ij} x_{ij} + \sum_{i=1}^{5} \sum_{k=i}^{5} \widetilde{a}_{ikj} x_{ij} x_{kj}, \ j = \overline{3,7} \qquad (7)$$

where $y_{R2}, y_{R3}, y_{R4,4a}$ are the catalyst volume at the output of reactors P-2, P-3 and P-4,4a accordingly; $y_j, j = 1{,}2$ are the volume of dry gas and water-containing gas (WCG) accordingly; $\widetilde{y}_j, j = \overline{3,7}$ are the qualitative indicators of the catalyst: the octane number (is no less than 86 according to the motor method); the fractional composition ($\widetilde{y}_4$ -10% distillate $\widetilde{y}_3$ on, no less than 70°C, $\widetilde{y}_5$ - 50% distillation, no more than 115°C); saturated vapour pressure ($\widetilde{y}_6$ is no more than 500mmHg); the resin content per 100ml of petroleum ($\widetilde{y}_7$ is no more than 5.0 mg); x_1 is the raw hydrogenation product at the output of the hydro-treatment unit in m^3/hour; x_2 is the volumetric flow rate in $hours^{-1}$; x_3 is the temperature of reactors P-2, P-3, P-4,4a in °C, x_4 is the pressure in reactors P-2, P-3, P-4,4a in kg/cm^2; x_5 is the ratio H_2/raw material (crude), H/m^3; a_{0j}, a_{ij}, a_{ikj} and $\widetilde{a}_{0j}, \widetilde{a}_{ij}, \widetilde{a}_{ikj}, i,k = \overline{1,5}$ are the regression coefficients which are being identified (□ is the symbol indicating uncertainty/fuzziness) for the constant terms; multiplying factors (x_{ij}), squared and cross-feed factors (x_{ij}, x_{kj}) accordingly.

In such a way, the models which describe the production volume at the output of the reforming block are constructed using experimental and statistical methods in the form of multiple regression models, and models describing the qualitative indicators of the production are constructed based on fuzzy data provided by specialists and experts in the form of fuzzy multiple regression equations. Model coefficients (3)-(7) are determined using known methods for parametric identification (using the Regress programme based).

The results of the model parametric identification, determining the catalyst volume at the reactors output (y_{R2}, $y_{R3,}$ $y_{R4,4a}$) and water-containing gas (y_2) are shown in the form of (8)-(11):

$$\psi_{P2}=\phi_1(\square_1,\square_2,\ldots,\square_5) = 0.39848\square\xi_1 + 12.15385\square\xi_2 + 0.03211\square\xi_3 - 0.98375\square\xi_4 + 0.01975\square\xi_5 + 0.00494\square\xi_1^2 + 9.34911\square\xi_2^2 - 0.00007\square\xi_3^2 - 0.03792\square\xi_4^2 + 0.00005\square\xi_5^2 + 0.22788\square\xi_1\xi_2 + 0.0001\square\xi_1\xi_3 + 0.00197\square\xi_1\xi_4 + 0.00049\square\xi_1\xi_5 + 0.03705\square\xi_2\xi_3 - 0.48615\square\xi_2\xi_4 - 0.00064\square\xi_3\xi_4 \qquad (8)$$

$$\psi_{P3}=\phi_1(\square_1,\square_2,\ldots,\square_5) = 0.39500\square\xi_1 + 12.10769\square\xi_2 + 0.03186\square\xi_3 - 0.98375\square\xi_4 + 0.01967\square\xi_5 + 0.00504\square\xi_1^2 + 9.31361\square\xi_2^2 - 0.00006\square\xi_3^2 - 0.04099\square\xi_4^2 + 0.00005\square\xi_5^2 + 0.22989\square\xi_1\xi_2 + 0.00010\square\xi_1\xi_3 + 0.00207\square\xi_1\xi_4 + 0.00049\square\xi_1\xi_5 + 0.03676\square\xi_2\xi_3 - 0.50448\square\xi_2\xi_4 - 0.00066\square\xi_3\xi_4 \qquad (9)$$

$y_{R4,4a}=f_1(x_1,x_2,\ldots,x_5)$ = 0.39898□x_1 + 12.07692□x_2 - 0.03158□x_3 - 1.02391□x_4+0.01962□x_5 +0.00507□x_1^2+ 9.28995□x_2^2 - 0.00006□x_3^2 - 0.04452□x_4^2 +0.00005□x_5^2 +0.23018□x_1x_2+0.00010□x_1x_3+0.00217□x_1x_4+0.00049□x_1x_5+0.03645□x_2x_3-0.52508□x_2x_4-0.00068□x_3x_4 (10) (11)

y_2 = $f_2(x_1,x_2,\ldots,x_5)$ = 500.0□x_1 +7142.8571□x_2 +10.101□x_3 - 1458.3333□x_4 +25.0□ x_5 +6.25□x_1^2 +5102.0408□x_2^2+0.0204□x_3^2 - 60.7639□x_4^2+0.0625□x_5^2+178.5714□x_1x_2 +0.2525□x_1x_3- 5.625□x_1x_4+15.625□x_1x_5 -297.619□x_2x_4-2.5252□x_3x_4-0.05051□x_3 x_5 -1.0417□x_4x_5

Identification of fuzzy coefficients $\tilde{a}_{ij}, i=\overline{0,6}$ and $\tilde{a}_{ikj}, i,k=\overline{0,6}$, $j=\overline{3,7}$ for the simultaneous equations (7) is based on the use of fuzzy set theory methods and □-sets.

Mathematical models, describing the dependency of the qualitative indicators of the catalyst on the input regime parameters $(\tilde{y},\ j=\overline{3,7})$ are identified in the following way:

y_3 = $f_3(x_{13},x_{23},\ldots,x_{53})$ = (0.5/0.43 + 0.75/0.433 + 1/0.435 0.75/0.437+0.5/0.44) x_{13} + (0.5/20.0769+0.75/20.07691+1/20.07692+0.75/20.07693 +0.5/20.07694) x_{23}+(0.5/0.05281+0.75/0.05282 +1/0.05283 +0.75/0.05284 + 0.5/0.05285) x_{33} - (0.5/0.72487+0.75/0.72495 + 1/0.72500 +0.75/0.72505 + 0.5/0.72513) x_{43} + (0.5/0.04221 + 0.75/0.04233 + 1/0.04243 + 0.75/0.04253 + 0.5/0.04266) x_{53}+0.75/0.04253+0.5/0.04266)x_{53}+(0.5/0.0052+0.75/0.0053+1/0.0054 + 0.75/0.0055+0.5/0.0056)x_{13}^2 - (0.5/15.4434 +0.75/15.4436 +1/15.4437 + 0.75/15.4439+0.5/15.4441) x_{23}^2+(0.5/0.000007 + 0.75/0.00005 + 1/0.00011 +0.75/0.00015 + 0.5/0.00020)x_{33}^2 - (0.5//0.0300+0.75/0.0301 + 1/0.0302 +0.75/0.0303 + 0.5/0.0304)x_{43}^2 + (0.5/0.000004 + 0.75/ 0.00005 +1/0.00010 + 0.75/0.00015 + 0.5/0.00022)x_{53}^2 + (0.5/0.00010 + 0.75/0.00017 + 1/0.00 022+0.75/0.00027+0.5/0.00034)$x_{13}x_{33}$+(0.5/0.00012+0.75/0.00020+1/0.000 27+0.75/0.00033+0.5/0.0004)$x_{13}x_{53}$ - (0.5/0.5572 + 0.75/0.5574+1/0.5576 + 0.75/0.5578+ 0.5/0.55814) $x_{23}x_{43}$ +(0.5/0.00005 + 0.75/0.00006 + 1/0.00008 + 0.75/0.00012 ++ 0.5/0.00016) $x_{33}x_{53}$

In the same way $\tilde{y}_4$ – 10% distillation, $\tilde{y}_5$ – 50% distillation, $\tilde{y}_6$ - the saturated vapour pressure and $\tilde{y}_7$ – the resin content per100 ml of petroleum are determined.

Using the given system models to model the functioning of the equipment in dialogue regime, it is possible to determine the optimal working regime for the installation and solve the optimisation tasks and make a recommendation for efficient process control. The modelling results for the installation, and a comparison of those results with other known results and experimental industrial data are shown in the table (see Table 1).

In the solution of the task of optimisation for multi-criterial objects such as technological systems for oil refining, a system of computer modelling and optimisation (CM&OS) using mathematical modelling of their working regimes is always useful. Such systems combine the advantages of modelling methods, optimisation methods and modern computer technology which speed up and improve the optimisation procedure. Below is the proposed structure for the CM&OS for technological installations for oil refining, by modelling of their working regimes. (see Figure 2):

Table 2 – Comparison of known results [20], results of modelling based on the proposed method and experimental data from the LG installation at Atyrau Oil Refinery.

Parameters, determined as the result of modelling	Known models: based on the Runge-Kutta method	Proposed Models	Experimental-Industrial Data
Useful product output from the hydro-treatment unit (hydrogenation product), % (mass)	94.1	95.3	95.0
Aromatic hydrocarbon content y_A, %	68.9	-	-
Unsaturated hydrocarbon content in the hydrogenation product, %	-	0.7005	$(0.8500)^L$
Sulphur content in the hydrogenation product, %	-	0.000046	$(0.000047)^L$
Water soluble acid and alkali content in the hydrogenation product, %	-	0.000003	$(0.000003)^L$
Hydrogenation product output from column K-1, m^3/hour	76.0000	79.5031	76.5575
Hydrogen bearing gas output from K-2, m^3/hour	1700	1700	1705
Raw hydrocarbon bearing gas output from column K-3, m^3/hour	1672	1670	1680
Output volume of raw gas mixtures from the heater P(heater)-101, m^3/hour	-	75.00	74.90
Temperature of the output flow from the heater P(heater)-101, ^oC	-	340	340
Useful product output from the reforming unit (catalyzator), %	94.5	95.5	95.0
Catalyst volume, m^3/hour	77.2	77.8	77.5
Octane number of the product (MM)		87	$(86)^L$
Fractional composition of the catalysator, ^oC: 10% distillation 50% distillation	 - -	 67 110	 $(68)^L$ $(114)^L$

Resin content in 100 ml of petroleum in mg	-	4.85	$(5)^L$
Flow from the output of reforming heater P(heater)-1, m^3/hour	-	77.85	77.60
Temperature at the output of heater P-1 (3^{rd} stage), ^oC	-	530	530

Note: The input and regime parameters for the process were almost identical, $()^L$ indicates that data was obtained in the laboratory.

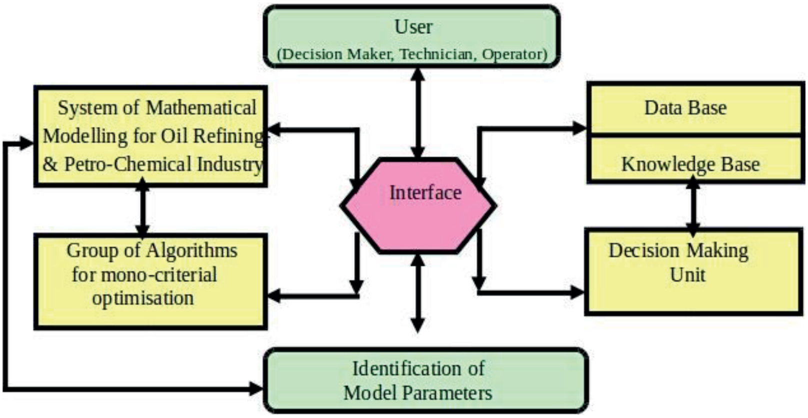

Figure 2. The structure for the CM&OS for regimes for technological installations for the oil refining and petro-chemical industries using mathematical modelling of their functioning.

Conclusion. The originality and novelty of the results of this work, lie in the fact that a generalised method has been proposed for the modelling of complex technological processes in conditions of uncertainty, which allows for the construction of an adequate model of complex objects using various types of data. In order to implement and use the proposed method in practice, a system of mathematical models for the reforming unit of the catalytic reforming installation has been developed. A structure has been created, and the main functional blocks have been proposed for a system of computer modelling and optimisation of technological processes in oil refining based on the modelling. The advantage of the proposed computer system is determined by the fact that it includes a complex system of algorithms and models, and also a convenient intellectual interface, which allows us to solve the task of modelling and multi-criterial optimisation of mutually dependent technological systems for industrial installations.

In such a way, based on systems and fuzzy set theory, probabilistic methods and methods of expert evaluation, for the first time ever, a generalised method for the construction of mathematical models for process systems in the oil refining industries has been developed which uses various types of data. The proposed method has been successfully implemented for the construction of mathematical models for the main blocks and units of the catalytic reformer at the Atyrau Oil Refinery.

Acknowledgment. *The work was performed with the financial support of the National Committee of the Ministry of Education and Science of the Republic of Kazakhstan under grant financing No AP08855680-Intelligent decision support system for controlling the operating modes of the catalytic reforming unit.*

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ISSN 2518-170X (Online),

ISSN 2224-5278 (Print)

Директор отдела издания научных журналов НАН РК *А. Ботанқызы*

Заместитель директор отдела издания научных журналов НАН РК *Р. Жәлиқызы*

Редакторы: *М.С. Ахметова, Д.С. Аленов*

Верстка на компьютере *Г.Д.Жадыранова*

Подписано в печать 25.07.2022.

Формат 70x90 $^{1}/_{16}$. Бумага офсетная. Печать – ризограф.

15,5 п.л. Тираж 300. Заказ 4.

Национальная академия наук РК

050010, Алматы, ул. Шевченко, 28, т. 272-13-19