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Models for Oil Refinery Waste Management Using Determined and Fuzzy Conditions

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Abstract: This study developed models to solve problems of optimisation, production, and consumption in waste management based on methods of system analysis. Mathematical models of the problems of optimisation and sustainable waste management in deterministic conditions and in a fuzzy environment were formulated. The income from production was maximised considering environmental standards that apply to the field of macroeconomics and microeconomics. The proposed approach used MANAGER software to formalise and solve the problem of revenue optimisation with production waste management to optimise the production of oil products with waste management at a specific technological facility of the Atyrau oil refinery in Kazakhstan. Based on the combined application of the principles of maximin and Pareto optimality, a formulation of the problem of production optimisation with waste management was obtained and a heuristic algorithm for solving the formulated fuzzy optimisation problem with waste management was developed.

Keywords: mathematical model; optimisation; sustainable waste management; mathematical programming; economic and environmental system; fuzzy information; heuristic method; maximin principle; Pareto optimality principle

1. Introduction

The irresponsible use of natural resources and environmental pollution has deteriorated the current quality of the environment and human health of the Republic of Kazakhstan. The major problems to be addressed in Kazakhstan caused by the activities of oil and gas, metallurgical, and other industries, are air pollution, water pollution, the accumulation of production and consumption waste, as well as the irrational use of biological diversity [1]. Consequently, the use of more effective levers is required to reduce the anthropogenic pressure on the environment, to utilise and reuse of waste in practice, for the sustainable management of these processes [2–5]. One such approach to address the issue of waste disposal and sustainable waste management is based on optimisation and management methods based on mathematical models using information technology [6].

Globally, the system of regulation and waste management has evolved in various ways [3,4,7], with issues of sustainable waste management strictly regulated both at the level of the European Union (EU) as a whole, as well as the individual member states [8]. The main management tools in EU legislation include regulations, directives, EU decisions and laws of EU member states, which are binding on all EU member states. Unlike EU regulations and decisions, which are instruments of direct action, the directive is introduced through national legislation, obliging the state party to take measures within a specified time period aimed at achieving the defined goals, but the choice of form and means to achieve these goals is determined by the states themselves. EU regulations and EU decisions are binding on all member states but do not require implementation in national legislation. If, along with the European regulations, national law is adopted, it supplements the provisions of the regulations. Thus, the priority of EU law is always higher than the national law [9].

The term "waste management" in current world practice refers to the organisation of waste management to reduce the impact on human health and the state of the environment by recycling and reusing [10]. Moreover, in recent years, these problems have been solved using mathematical methods and means of information technology has become a more promising and effective approach [11,12]. "Sustainable management" takes concepts from sustainability and synthesises them with management concepts. Sustainability is based on the environment, the needs of present and future generations, and on economics, nutrition, and ecology [13].

The State Cadaster of waste production and consumption can be considered as an accounting system that allows complete information to be obtained about waste management in any section. This inventory, in accordance with the Environmental Code of the Republic of Kazakhstan №212-III LRK from 9th January 2007, should reflect all stages of waste management and is maintained in order to provide government agencies and interested parties with information for assessment, forecasting, technological development, economic, legal, and other decisions in relation to environmental protection, as well as conducting national comprehensive accounting and waste management. Thus, for the effective management of production waste, it is necessary to create a waste management system, that is, a set of measures for the collection, transportation, recycling, recycling or disposal of waste, as well as monitoring and managing the listed processes based on mathematical methods and information technology tools.

Currently, the environmental policy in the Republic of Kazakhstan is within the framework of the "Zhasyl Damu" sectoral programme and the Strategic Plan of the Ministry of Energy of the Republic of Kazakhstan. However, it has not yet been possible to significantly minimise the negative impact of environmental pollution due to production and consumption waste on ecological systems and public health.

The aim of this study was to investigate features of sustainable waste management in the field of environmental protection and develop an approach to effectively solve problems of sustainable waste management using mathematical methods, including methods of theories of fuzzy sets, which overcome problems of deficit and fuzziness of the initial information [14,15]. The following objectives were set to achieve this goal: to develop an environmental and economic model for the management of production and consumption waste, and to formulate models of the problem of optimisation and waste management in different conditions, in deterministic conditions and in conditions of unclear initial information, and to propose effective methods for solving them.

2. Literature Review and Comparative Analysis

Analyze some of the main research papers that study the issues of waste management using mathematical methods. In works [1,3], models of the problem of optimizing production are considered taking into account environmental criteria, but these models do not take into account the restriction on "production purity", i.e., environmental standards that determine the values of permissible waste for each type of pollution. Therefore, production will often have to pay large fines for exceeding standards. In the proposed paper the following conditions are added to the model of production optimization and waste management: $\overline{w} \leq \overline{w}^*$, where $\overline{w}$—pollution vector; $\overline{w}^*$—a vector of environmental standards, that is, the permissible waste for each type of pollution. The novelty of the augmented model is that the additional condition allows to control and manage waste so that the amount of pollution does not exceed the permissible waste for each type of pollution. This in turn does not admit environmental fines for exceeding the established standards.

Regarding the use of mathematical methods to address issues of waste management, Kornilova and Pazyuk [16] proposed mathematical modelling for the processes of utilisation and recycling of waste using the example of recycling used car tyres. Using the static modelling method, they considered options for solving two problems: placing points of specialisation and concentration of processing throughout the region or in one place. The mathematical models take into account risk factors that affect the parameters of the volume, price and costs of the waste recycler. To form a rational organisational and technological structure of the auto recycling system and the concept of strategic management of motor waste in the region in [17], balance models for the function of the regional auto recycling system were formed, taking into account the material and financial components.

A group of scientists within the framework of the project, "Development of the Model and Technologies of Logistics of the Communal Waste Transport" [18], solved the problem of choosing an optimal solid waste management system in the centre of Nis. The goal of optimization, i.e., the target function in this problem was the function of maximizing the efficiency of waste utilization and recycling. Due to the complexity of the system and its variable performance, a multicriteria optimisation method and hierarchy analysis were used. In [19,20], American researchers examined the problems of drilling waste utilisation and approaches to their solution using stochastic, probabilistic models.

In the application of the stochastic approach, probabilistic methods for solving such problems are not justified. This is because in conditions of uncertainty of the fuzzy nature of the information, the possibility of conducting experiments under the same conditions are not satisfied [21,22]. In this regard, the development and application to solve problems of optimisation and waste management in a fuzzy environment is currently a promising and relevant direction [23–25]. Interesting results were obtained in sustainable waste management when drilling oil wells in marine conditions using a fuzzy inference system [25].

It is also worth noting the works [26,27] in which the problems of waste management using fuzzy sets are solved. For example, in [26], a three-step methodology for initiating an effective electronic waste management system in Turkey is investigated, and in [27], an intuitive fuzzy CODAS (combinative distance-based assessment) approach based on MCDM is proposed for finding an authorized dismantling center.

The novelty of the proposed heuristic approach in this paper in comparison with previous researches is that the proposed method for solving the problem of optimizing production and waste management under conditions of fuzzy restrictions takes into account the experience, knowledge, and preferences of the DM and provides a more effective solution to fuzzy problems.

3. Model Setup

With the help of systems theory and system analysis, production systems can be represented as a complex system that has properties, which can be described by mathematical models. The main properties of production systems include [1,9,11,12,15,16,19,28,29]:

Divisibility: The system consists of several economic, environmental, social and other parts, each of which has its own goals and functions, while a simple combination (not within the system) of components will not be identical in its properties to the whole system.

Integrity: The system has the fullness of properties and functions only as a single whole [12,15].

Connected components: All components, for example, economic, environmental components of the system are interconnected and affect each other [16,19].

Emergence: The properties of the production system are manifested only as a result of the interaction of its economic, environmental, and other components [28,29].

We discuss the complexity of object of the research and the problem being solved. Production systems, including the object of research in this work, the technological complex of primary oil processing, are complex objects consisting of many interconnected and interacting units. The quality of such complex objects is affected by many different parameters, and complex objects are often characterized by multi-criteria and uncertainty due to the lack and vagueness of the source information [30–32].

The complexity of the problem of optimizing production of complex oil processing in the conditions of rigid environmental requirements that produce different oil products taking into account the available resources in that it is necessary to consider not only the payments for environmental pollution, but also environmental standards, acceptable waste, maximum allowable concentrations of each type of pollution, i.e., "purity production". In this regard, to solve such complex problems, it is necessary to apply mathematical methods and models, methods of mathematical programming, and in conditions of a lack of fuzzy initial information, methods of expert assessments and fuzzy set theories.

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Therefore, when optimising and managing production facilities, the main management criteria are in addition to economic (profit, productivity, volume and quality of products, etc.) and environmental criteria (volume of waste, harmful emissions, indicators of utilisation and, quality of waste management). Moreover, as a rule, in a certain area of the solution, where more effective solutions are found, for example, the Pareto set, these criteria are contradictory. In this area of improving the value of one criterion, it is possible only due to the deterioration of the value of other criteria. Thus, the problems investigated and solved in this paper relate to multicriteria problems according to economic and environmental criteria. Accordingly, methods of mathematical modelling [21,30], mathematical programming, multicriteria optimisation [31–33], as well as methods of multicriteria selection and decision-making on optimal waste management [34–36] were used to solve such problems. In addition, when formulating and solving waste management problems in a fuzzy environment, expert estimation methods [37,38] and the theory of fuzzy sets [21,24,27,33,39] were used.

START developing a system of mathematical models

** Defining evaluation and comparison criteria models that can be built for each element of the production system.

** Use the selected criteria to conduct an expert assessment of possible model types for each element of the system and determine the optimal model type for each element based on the sum of the criteria value.

*** If the theoretical data for describing the work of individual elements is sufficient and the deterministic model is effective on the sum of evaluation criteria, then deterministic models are built for this aggregate based on the analytical method.

*** If statistical data are sufficient to describe the operation of an individual element or collection of such data is possible, and the statistical model is effective based on the sum of evaluation and comparison criteria, then statistical models of this element are based on experimental statistical methods.

*** If theoretical and statistical data to describe the working element of the system is insufficient, the collection of such data is economically impractical, and the collection of fuzzy information describing the operation of the unit and the process running in it is possible, the sum of evaluation and comparison criteria the fuzzy model is effective, then for this aggregate, based on the methods of fuzzy set theory, fuzzy models are constructed.

*** If theoretical, statistical data, and fuzzy expert information to describe the operation of a separate element of the system are not sufficient and the collection of such data is impractical, then for this aggregate, based on a combination of collected information of various types (theoretical, statistical, fuzzy), a combined model is built based on available information of various types.

** Checking the model adequacy condition. If the adequacy condition is met, i.e., $S = \left(y^M - y^E\right)^2 \leq S_R$, where S and S_R, are accordingly, the adequacy criterion and its acceptable value, then y^M and y^E, the values of the output parameters obtained from the model and experimentally, with the same values of the input parameters, the models are considered adequate. Otherwise, find out the reason for the inadequacy and return to the stage of building the model to address the issue of ensuring the adequacy of the model.

* END of model development
START of statements and solving the problem of optimization and management of production waste based on the developed models.

** Definition of the optimization and control criteria.

** Identify existing resource constraints and regulatory constraints.

** Formalization and formulation of the problem of waste optimization and management.

** Selection or development of a method for solving the formulated optimization problem.

** Algorithmization and software implementation of the method for solving the optimization problem.

** Solving the optimization problem of searching for optimal values of criteria, taking into account the imposed restrictions, based on the developed mathematical models.

*** In the conditions of fuzzy initial information, the problem is solved on the basis of the experience, knowledge, and intuition of the DM, experts, i.e., using fuzzy information taking into account the preferences of the DM.

* END of the optimization problem solution.
{- - - - - - - - Output results ————–}

* The OUTPUT of the optimization results.
End of the method.

4. Results

4.1. Mathematical Models of Problems of Optimisation and Waste Management

Given the critical natural capital N^*, the condition of sustainable management can be supplemented by a restriction on the exhaustion of this quantity in time. For a production function that does not decrease in time, the arguments are the aggregated variables of labour L, capital K, and natural resource N [1,8]:

$$F_t(K, L, N) \leq F_{t+1}(K, L, N) \tag{1}$$

To comply with the condition of non-decreasing in time values N^*:

$$N_t^* \leq N_{t+1}^* \tag{2}$$

as well as the condition for the partial replacement of natural capital N with an artificial N^S or non-renewable resource with a renewable resource:

$$N_t = N_t^* + N_t^S \tag{3}$$

The problem of optimising production under certain environmental standards is then formulated as a mathematical programming problem [18]. In this paper, this problem is formalized and presented as a mathematical programming problem.

Let $F(x_1, x_2, \ldots, x_n)$ be the objective function characterising the production of n types of products using the necessary resources. Assuming that there are m types of pollution from a given production, which are given by the matrix of pollution intensities:

$$C_p = \begin{pmatrix} C_{11} & C_{12} & \ldots & C_{1n} \\ C_{21} & C_{22} & \ldots & C_{2n} \\ \ldots & \ldots & \ldots & \ldots \\ C_{m1} & C_{m2} & \ldots & C_{mn} \end{pmatrix} \tag{4}$$

$c_{ij} > 0$ is the amount of j—the pollution produced in the production of the i-th product, then, the pollution vector $\overline{w}$ is determined by the formula:

$$\overline{w}^T = C_p \overline{x}^T \text{or } w_k = \sum_{j=1}^{n} c_{kj} x_j,\ k = \overline{1, m} \tag{5}$$

where $\overline{x}$ is the product line-vector using appropriate resources. We introduce a matrix A, consisting of coefficients of resource constraints and a vector of constraints, $\overline{b}$ is determined by production capabilities [18]. In this paper, we have introduced a vector of environmental standards, $\overline{w}^*$ which is the allowable waste for each type of pollution. These standards are usually set according to existing standards for maximum permissible concentration (MPC) of pollution.

Then, we can write the mathematical model of the output optimization problem as follows:

$$F(x_1, x_2, \ldots, x_n) = F(\overline{x}) \to \max \tag{6}$$

on an admissible set:

$$\begin{cases} x \geq 0,\ z \geq 0, \\ A\overline{x}^T \leq \overline{b}^T \\ \overline{w} \leq \overline{w}^* \end{cases} \tag{7}$$

Unlike traditional optimisation models, the permissible set of which is formed only by the first two production Relations (7), this model also includes a restriction on "clean production", i.e., the last relation in (7): $\overline{w} \leq \overline{w}^*$, which means the amount of pollution should not exceed the allowable waste for each type of pollution. To meet the last condition in Relation (7), which in the expanded form, according to Formula (5), has the form of restriction for each type of pollution, we write:

$$\sum_{j=1}^{n} c_{kj} x_j \leq w_k^*,\ \ k = \overline{1, m} \tag{8}$$

Then, the production is necessary to make a choice of more advanced technologies or to replace "dirty" resources with cleaner ones, otherwise, due to Restrictions (8), the permissible volumes of production $\overline{x}$ may be so insignificant that it will not be possible to provide the desired values of economic criteria, for example, the maximum income level.

Models (6) and (7) refers to the field of macroeconomics, when output can be identified with the gross domestic product (GDP) of a country or with the gross output of a region, then Condition (8) is the management of technological policy.

To take into account the environmental factor in microeconomics, we propose moving to cost expressions in the objective function and payment for exceeding pollution standards [1,3,31]. Let p be the aggregated price of the manufactured products and the components of the vector:

$$z = (z_1, z_2, \ldots, z_m) \tag{9}$$

meaning the costs of eliminating pollution if the relevant standards are exceeded, i.e., if the third condition in (7) is violated. Then, the income function from the output $F(\overline{x})$ has the form:

$$P = pF(\overline{x}) - \overline{z}\,\overline{\delta}, \tag{10}$$

where $\overline{\delta}$ refers to the pollution charge "inclusions" vector included in this work:

$$\delta_j = \begin{cases} 0, \; w_j \le w_j^*, \\ 1, \; w_j > w_j^*. \end{cases} \quad j = \overline{1, m} \tag{11}$$

where $\overline{w}$ denotes the pollution vector defined by Formulas (4) and (5), while w_j^* the maximum permissible pollution vector components:

$$\overline{w}^* = \left(w_1^*, w_2^*, \ldots, w_m^*\right) \tag{12}$$

In order to simplify the task, we can assume that payments for environmental pollution are already included in the payment for environmental management, i.e., the second term in the income Function (10) with a minus sign is accepted as payment for the excess load on the environment. Therefore, the income Function (10) can be considered as a production function, the arguments of which are the volume of production $\overline{x}$, pollution $\overline{w}$, maximum permissible norms $\overline{w}^*$, and payments for environmental pollution $\overline{z}$.

Then the model for optimising income from product release using a vector with a $\overline{x}$ technology characterised by a production function $F(\overline{x})$ is determined as follows: Find the maximum of Function (10), taking into account Equations (11) and (9) on an admissible set of solutions

$$\begin{cases} \overline{x} \ge 0, \\ A\overline{x}^T \le \overline{b}^T \end{cases} \tag{13}$$

given the constraint (12) on the vector $\overline{w}$.

Thus, the revenue optimisation model with sustainable waste management (10)–(12) is universal and can be used for the purposes of microeconomics at the level of any enterprise, industrial complex, industrial output.

Consider an example of applying the proposed approach to formalisation and solving the problem of revenue optimisation with waste management of a specific facility. For this purpose, we present the data of a technological facility to produce various fuels during oil refining at the Atyrau oil refinery [38]. The primary processing unit of this plant produces different types of fuel, mainly diesel fuel (1-type product) and petrol (2-type product). The production of these petroleum products is described by restrictions on reagents, on the consumption of thermal energy, as well as the costs of eliminating pollution $z = (z_1, z_2)$ (z_1—air pollution, z_2—water pollution) in case of violation of the third condition (7) and pollution charges δ_j, $j = 1, 2$ which are determined by Formula (11).

Based on the Atyrau refinery data, it was found that in the object under study, during the production of units (1 tonne) of oil products of the 1st and 2nd type, respectively, the values of air and water pollution in monetary terms are approximately equal: z_1 = 65 thousand tenge (tg); z_2 = 58 thousand tenge. Taking into account environmental standards and based on Expression (11), pollution charges are determined as follows:

$$\delta_j = \begin{cases} 0, \; (c_{j1}x_1 + c_{j2}x_2) \le w_j^*, \\ 1, \; (c_{j1}x_1 + c_{j2}x_2) > w_j^*. \end{cases} \quad j = \overline{1, m}$$

where c_{j1}, c_{j2}accordingly, the amount of j-th pollution in the production of products of the 1st and 2nd types. Processing of the statistical data regarding the amount of 1st and 2nd pollution produced during the development of a unit of the i-th product, a matrix of pollution intensities was identified by Formula (4) [1,40]:

$$c_p = \begin{pmatrix} c_{11} & c_{12} \\ c_{21} & c_{22} \end{pmatrix} = \begin{pmatrix} 8 & 9 \\ 7 & 8 \end{pmatrix}.$$

For the production of 1 tonne of a product of the 1st type, 4 kg of reagents are required, and for the production of 1 tonne of a product of the 2nd type, 5 kg of reagents. The refinery can receive from their suppliers up to 100 kg of reagents in a week. To produce 1 tonne of diesel fuel, 12 units of thermal energy are required and for 1 tonne of petrol, 10 units. The amount of thermal energy generated and supplied in the week is 250 units. There is an opportunity for a higher price to buy additional reagents and additionally receive thermal energy. The price of 1 tonne of oil products of the 1st and 2nd type respectively is 150 thousand tg and 170 thousand tg.

These numerical data were obtained from the Accounting and Analysis Department of the Atyrau refinery.

Let x_1 and x_2 be the number of products, respectively 1 and 2 types, produced a week. Then, the income function, i.e., the objective function that needs to be maximised can be written as:

$$F(x_1, x_2) = 150x_1 + 170x_2$$

In addition, x_1 and x_2 express the amount of produced petroleum products of type 1 and 2, they must be positive, i.e., $x_1 \geq 0,\ x_2 \geq 0$. To determine the aggregate price of manufactured products, taking into account the opinions of experts, weights of diesel fuel and petrol were determined to evaluate their importance: $\gamma_1 = 0.3$; $\gamma_2 = 0.7$. Given the importance of fuels, the aggregated price of manufactured products $p = 0.3 \times 150 + 0.7 \times 170 = 164$ thousand tg. Then, considering the aggregated price of manufactured products, the objective function has the form: $pF(x_1, x_2) = p(x_1 + x_2) = px_1 + px_2$. Restrictions on reagents and on thermal energy can be mathematically written in the form of the following inequalities:

$$4x_1 + 5x_2 \leq 100(\text{for reagents})$$

$$12.5x_1 + 10x_2 \leq 250(\text{for thermal energy})$$

Given the limitation of costs for eliminating atmospheric pollution (z_2) and wastewater pollution (z_2) in case of violation of the third Condition (7) and the limitation on pollution charges $\delta_j,\ j = 1, 2$, the task of optimising production according to economic and ecological criteria and requirements, taking into account sustainable waste management, can be written in the form of a standard mathematical programming problem [31]:

$$\max(pF(x_1, x_2) - (z_1\delta_1 + z_2\delta_2)), \tag{14}$$

$$4x_1 + 5x_2 \leq 100 \tag{15}$$

$$12.5x_1 + 10x_2 \leq 250 \tag{16}$$

$$x_1 \geq 0,\ x_2 \geq 0 \tag{17}$$

Payments for environmental pollution are already included in the payment for environmental management in the objective Function (14) of the obtained mathematical programming task, which allows managing waste. In this problem, the second term in the income function with a minus sign is accepted as payment for the excess load on the environment in the form of production waste. Based on the above information, it is possible to disclose and specify the objective function (14) as follows:

$$\max(pF(x_1, x_2) - (z_1\delta_1 + z_2\delta_2)) = \max(164 \cdot (x_1 + x_2) - (65\delta_1 + 58\delta_2))$$

where δ_1 and δ_2 are determined from the condition:

$$\delta_j = \begin{cases} 0, & (c_{j1}x_1 + c_{j2}x_2) \leq w_j^*, \\ 1, & (c_{j1}x_1 + c_{j2}x_2) > w_j^*. \end{cases} \quad j = \overline{1,m}$$

At the Atyrau Refinery, for the considered oil products, the values of permissible waste are: $w_1^* = 60$; $w_2^* = 55$. Then, using the above data, the problem of optimising production and waste management (14)–(17) can be rewritten as the following mathematical programming problem:

$$\max(164x_1 + 164x_2) - (65\delta_1 + 58\delta_2)) \tag{18}$$

$$4x_1 + 5x_2 \leq 100 \tag{19}$$

$$12x_1 + 10x_2 \leq 250 \tag{20}$$

$$x_1 \geq 0,\ x_2 \geq 0 \tag{21}$$

$$\delta_1 = \begin{cases} 0, & 8x_1 + 9x_2 \leq 60, \\ 1, & 8x_1 + 9x_2 > 60. \end{cases} ;\delta_2 = \begin{cases} 0, & 7x_1 + 8x_2 \leq 55, \\ 1, & 7x_1 + 8x_2 > 55. \end{cases} ; \tag{22}$$

Since, in the problem (18)–(22), the objective function and all the restriction functions are linear, it is possible to use well-known methods for solving linear programming problems to solve it.

To solve the formulated linear programming problem, one can use software packages that programmatically implement methods for solving mathematical programming problems, including the simplex method, for example, among the well-known software packages such as "MANAGER", developed in England (there is a Russian version), "simplex method", "optimization" (Russian software products), CAE (computer aided engineering) (Germany), Mathematica, and MathCAD. Russian programs allow one to solve a narrower class of problems with a limited number of restrictions functions. Other programs are more complex to use and require many settings for defining and entering initial data, although they have good graphical interfaces. We have selected "MANAGER" among these software packages as the most convenient to use, having a high speed of calculation and requiring a minimum of requirements for the characteristics of the computer. In addition, this software product is the most versatile and suitable for solving optimization problems of almost any size and type, and also has a fairly simple and complete hint system.

Based on the application of the MANAGER program package, in which the methods for solving optimisation problems and decision-making, including mathematical programming methods, are implemented, the results of solving the formulated problem of production optimisation and waste management are obtained (18)–(22).

The optimal volumes of oil products produced, i.e., diesel fuel and petrol are equal to:

$$x_1 = 12.5; x_2 = 10$$

In this case, the maximum profit is 3690 thousand tg and the available resources, reagents and thermal energy, described by restrictions (19) and (20) are fully used:

$$4 \times 12.5 + 5 \times 10 = 100; 12 \times 12.5 + 10 \times 10 = 250$$

As a result of additional calculations, we determine:

$\delta_1 = 1$ and $\delta_2 = 1$, as well as $8x_1 + 9x_2 = (8 \times 12.5 + 9 \times 10) > 60$ and $7x_1 + 8x_2 = (7 \times 12.5 + 8 \times 10) > 55$.

Based on the additional calculations, we determine the final solution to the problem of optimising the production of petroleum products taking into account the amount of waste (18)–(22):

The final decision i.e., maximum weekly income from the production of fuels of the 1st and 2nd type: diesel fuel $x_1 = 12.5$ and petrol $x_2 = 10$, minus pollution charges, i.e., for discarded waste:

$$\max(164x_1 + 164x_2) - (65\delta_1 + 58\delta_2)) = 3690 - (65 + 58) = 3567 \text{ thousand tg.}$$

At the same time, for unused resources, i.e., no remaining resources, the positivity Condition (21) is satisfied, i.e., $x_1 \geq 0,\ x_2 \geq 0$.

In the above example, a deterministic version of the solution to the problem of optimising production and sustainable waste management was implemented.

For calibration and verification of the used model, i.e., correction of the structure and parameters of the model, an iterative process is carried out, which consists of several stages [41]:

1. Global model change, such as changing the model structure, introducing new equations, changing the types of equations, etc.
2. Local changes, in particular, changes in certain distribution laws of simulated random variables.
3. Changes to special parameters called calibration parameters.

In this paper, in order to correct the model in order to meet the requirements for accuracy with real data, the obtained simulation results are compared with the possible values of real data and if appropriate, presented to the technologist and ecologist of the Atyrau refinery, who are the final decision makers (DM). If the simulation results correspond to real data and fully satisfy the DM, the models are considered calibrated and verified.

According to the calibration method, after the third iteration stage, and after correcting the values of the elements of the matrix of pollution intensity, the results corresponding to the real values were obtained and are listed above; these completely satisfied the DM.

4.2. Tasks and Methods of Decision-Making on Waste Management in a Fuzzy Environment

Making decisions (MD) involves evaluating possible options (alternatives) and choosing the best according to given criteria [35,42–44]. The solution of the decision-making problem is reduced to identifying and studying the preferences of the decision-maker (DM), building on this adequate model [45–48] to select the best alternative.

The MD task for waste management in a fuzzy environment can be formulated as mathematical programming problems with fuzzy elements [21,33]. Fuzzy mathematical programming (FMP) understands that the task is to use the objective function or the vector of entire functions, which should optimise and use a system of unequal or equal conditions; restrictions, specific or all elements of the task (requirements, restrictions, information about their importance and necessity).

Here is the statement of the decision-making problem in the form of an FMP problem, which is suitable for solving problems with strict environmental requirements based on the application of a maximin compromise scheme to criteria, i.e., a guaranteed result.

Let $\mu_0(x) = (\mu_0^1(x), \ldots, \mu_0^m(x))$ be normalised criteria vector $f_i(x),\ i = \overline{1,m}$, estimating the amount of income from the sale of manufactured products by a technological facility. Suppose that for each fuzzy constraint, including according to environmental requirements $\varphi_q(x) \tilde{>} b_q,\ q = \overline{1,L}$ the function of belonging to its implementation is built $\mu_q(x),\ q = \overline{1,L}$. It is assumed that either a number of priorities for local criteria $I_k = \{1, \ldots, m\}$ and constraints $I_r = \{1, \ldots, L\}$ are known, or a weight vector that reflects the mutual importance of criteria $\gamma = (\gamma_1, \ldots, \gamma_m)$ and $\beta = (\beta_1, \ldots, \beta_L)$ constraints. Then, by combining various compromise decision-making schemes for criteria and constraints and modifying them to work in a fuzzy environment, it is possible to formulate and solve various MD problems in a fuzzy environment [25,33].

Assuming that decision-makers can determine the priorities of local criteria and select the main criterion from the set of criteria, and the remaining criteria can be set to boundary values that they must satisfy. In addition, let the number of restrictions be no more than 7 ± 2 and decision-makers can evaluate the weighting factors of these restrictions. Then, the statement of the PR problem when controlling the operating conditions of the production facility according to economic and environmental criteria based on the principles of maximin, MM (for the criterion), and Pareto optimality, PO (for constraints), can be written as follows:

$$\max_{x\in X} \mu_0^1(x), \tag{23}$$

$$X = \{x : \arg\max_{x\in\Omega} \min_{i\in I_0}(\gamma_i \mu_0^i) \wedge \operatorname{argmax}_{x\in\Omega} \sum_{q=1}^{L} \beta_q \mu_q(x) \wedge \sum_{q=1}^{L} \beta_q = 1 \wedge \beta_q \geq 0, \\ I_0 = \{2, \ldots, m\},\ q = \overline{1,L}\} \tag{24}$$

In the MD problem, when setting (23)–(24), the main criterion with priority 1 is maximised, the remaining criteria are introduced into the constraint according to the maximin principle with predefined boundary values, and fuzzy constraints are taken into account based on the PO principle [49–51].

When solving fuzzy problems, the known methods mainly use the idea of converting the original fuzzy problem to clear problems, for example, based on a set of level a. But this approach leads to the loss of a significant part of the collected initial fuzzy information, which represents the formalized knowledge, experience, judgment and intuition of experts in the subject area, DM, i.e., heuristics. Such fuzzy information is usually more informative and allows us to take into account the complex relationship between the various parameters of the object under study, which is not formalized by deterministic methods. In this regard, it is recommended to take into account fuzzy information, and the use of a heuristic approach in solving optimization and process management problems is necessary and promising [28].

The main idea of the heuristic approach to solving problems in conditions of scarcity and fuzziness of the initial information is that the knowledge, experience and intuition of a person (DM, expert) is taken into account and used in solving the problem, i.e., formalized fuzzy information using fuzzy set theories [19,21–25].

We describe the main steps of the developed heuristic algorithm for solving the problem of optimization of production with waste management in the statement (23)–(24).

To motivate the approach to solving the problem of fuzzy optimization using the heuristic method, it can be noted that the known approaches to solving such problems based on sets of the level α leads to the loss of a significant part of the original available fuzzy information and the proposed approach using the heuristic method allows the maximization of the experience, knowledge and intuition of the DM, experts, i.e., available fuzzy information. Such fuzzy information allows for a more adequate description of the problem in a fuzzy environment and thus provides effective solutions based on the preferences, experience and knowledge of the DM.

Algorithm *MM + PO*:

(1) The DM determines the values of the weighting coefficients for the local criteria $\mu_0^i(x), i = \overline{1,m}$: $\gamma = (\gamma_1, \ldots, \gamma_m),\ \sum_{i=1}^{m} \gamma_i = 1,\ \gamma_i \geq 0, i = \overline{1,m}$.
(2) If the criteria $\mu_0^i(x)$, the weight vector γ are fuzzy, then term sets are determined for them and membership functions are constructed.
(3) With the involvement of the DM, the values of the weighting coefficients for the restrictions are determined $\mu_q(x),\ q = \overline{1,L}$: $\beta = (\beta_1, \ldots, \beta_L),\ \sum_{q=1}^{L} \beta_q = 1,\ \beta_q \geq 0, q = \overline{1,L}$.
(4) Set $p_q,\ q = \overline{1,L}$—the number of steps along each q-th coordinate.
(5) $h_q = \frac{1}{p_q},\ q = \overline{1,L}$ are calculated as step values for changing the coordinates of the weight vector β_q.
(6) Variation of coordinates on segments [0,1] with steps h_q a set of weight vectors is constructed $\beta^1, \beta^2, \ldots, \beta^N, N = (p_1 + 1) \cdot (p_2 + 1) \cdot \ldots \cdot (p_L + 1)$.

(7) Based on expert procedures, the term set is determined, and the membership functions of constraints are constructed $\mu_q(x),\ q = \overline{1, L}$.

(8) Based on the object model, the maximisation problem is solved $\max\limits_{x \in X} \ \mu_0^1(x)$ (23) on the set X, which is determined by the expression (24). Current decisions determined $x(\gamma, \beta),\ \mu_0^1(x(\gamma, \beta)), \ldots, \mu_0^m(x(\gamma, \beta)), \mu_1(x(\gamma, \beta)), \ldots, \mu_L(x(\gamma, \beta))$.

(9) The resulting decision is presented to the DM. If the current results do not satisfy the DM, then they are assigned new values or the values γ and (or) β are adjusted and return to step 2. Otherwise, go to step 10.

(10) The search for a solution is terminated, the results of the final decision-making decision are displayed: providing optimal solutions, i.e., maximum income when fulfilling all the fuzzy restrictions: $x^*(\gamma, \beta)$; optimal values of local criteria $\mu_0^1(x^*(\gamma, \beta)), \ldots, \mu_0^m(x^*(\gamma, \beta))$ and the maximum degree of fulfilment of fuzzy restrictions $\mu_1(x^*(\gamma, \beta)), \ldots, \mu_L(x^*(\gamma, \beta))$.

In the proposed heuristic method when solving the fuzzy optimization problem, the final result, i.e., the best solution is made by the DM based on their knowledge, experience and intuition. The DM is a specialist-an expert in the subject area, of the problem being solved. Accordingly, the DM is able to assess the real situation in the production and makes more appropriate decisions based on their preferences. The final acceptance procedure is performed iteratively in the DM-computer dialog. The calculation results are presented in a convenient form for the DM by the computer, which analyzes the solutions, and in a case of unsatisfactory results, changes the values of some parameters to improve the solution, and the procedure for finding the best solution continues. If the obtained solutions satisfy the DM, then it makes the best final decision based on its preference and taking into account the correspondence with real data of real production.

For a clear description of the methodology of the fuzzy approach to solving the optimization problem in a fuzzy environment, we will give a more detailed description and explanation of some of the main points of the proposed MM + PO algorithm. The algorithm is based on using the Maximin principle adapted for fuzziness for the criterion, i.e., the most important criterion with priority 1 will be maximized, and the guaranteed (maxmin) values of the remaining criteria are taken into account as part of the restrictions. In this algorithm, the values of fuzzy constraints, i.e., the maximum degrees of their fulfillment, are taken into account based on the Pareto optimality principle for expression (24).

A clearer representation of the proposed algorithm is given in the flowchart in Figure 1.

In order to validate the proposed methods, i.e., to prove that the user's (the DM's) requirements, tests were carried out when solving test and real problems for optimizing the production of various petroleum products taking into account the available resources and the vector of environmental standards $\overline{w}^*$, and taking into account penalties for violations of standards due to excess of permissible waste. At the same time the obtained results fully satisfied the DM (the technologist of the primary processing shop and the chief ecologist of the Atyrau refinery). These results were given above (Section 4.1). Thanks to the results obtained, the Atyrau refinery managed to save a significant amount (about 2500 thousand tenge), which they had often paid as a fine for exceeding the permissible waste.

In the proposed heuristic method for solving the problem in fuzzy, the final results are selected by the user, i.e., the DM, who chooses the best solution taking into account his preference, the existing production situations and regulatory requirements. In this case, the best solution is made in iterative mode, by consistently improving the results based on the "DM-computer" dialog. This mode provides results that satisfy the DM, which is a validation of the heuristic method.

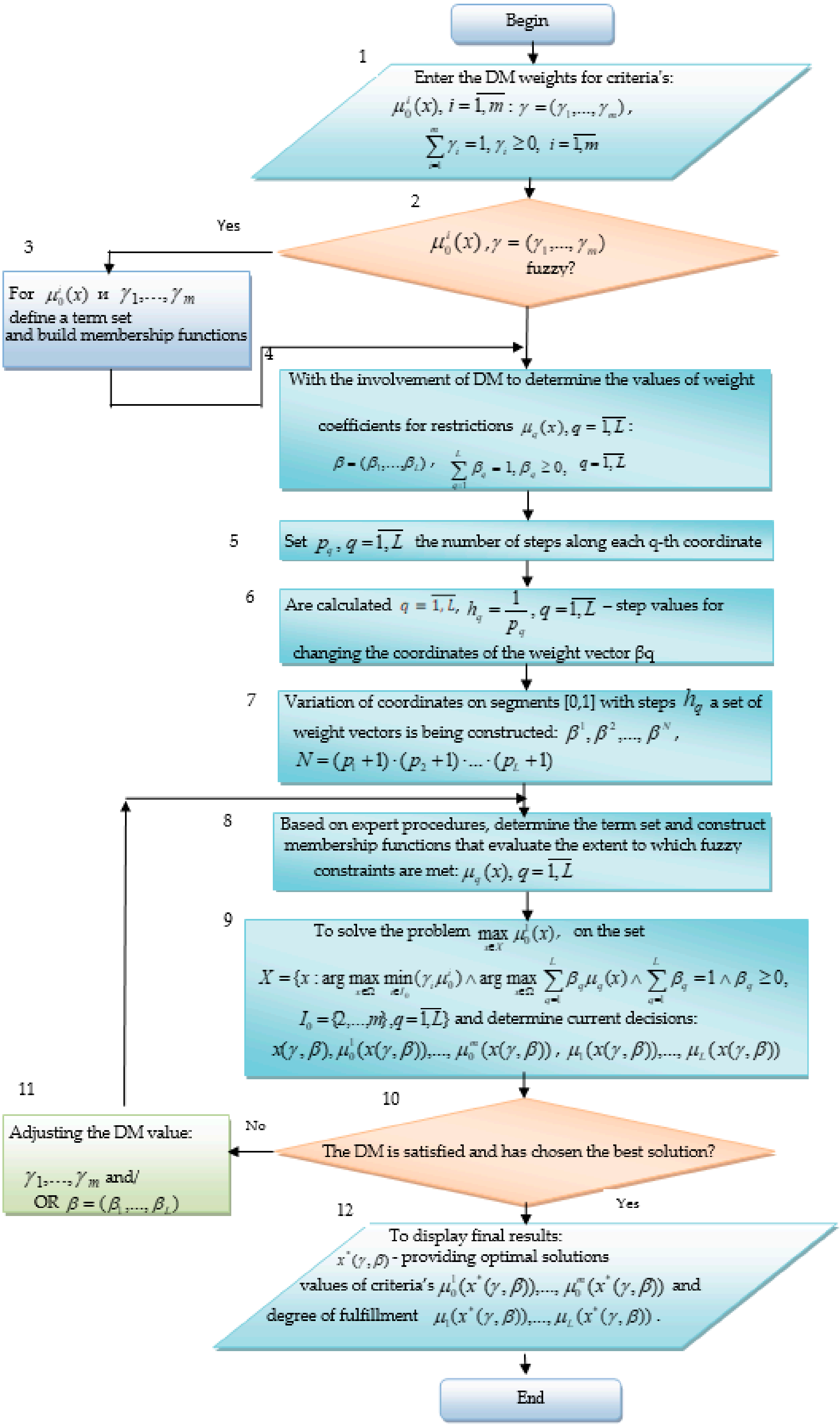

Figure 1. Flowchart of a heuristic algorithm based on the principles of MM + PO.

5. Discussion

A graphic illustration of the mathematical model of the production optimisation problem (6)–(7) is shown in Figure 2. Limitations for each type of pollution (8): $\sum_{j=1}^{n} c_{kj}x_j \le w_k^*,\ \ k = \overline{1, m}$ the figure shows the shaded area and they, apparently, reduce the feasible set of solutions on which the optimal solution is sought. It is of note that the type and size of this region depend on the coefficients c_{ij}. i.e., from the technology of resource use. With "dirty" technologies, the narrowing of the range of acceptable solutions is very significant (Figure 2a); the use of saving "clean" technologies slightly narrows the scope of feasible solutions (Figure 2b).

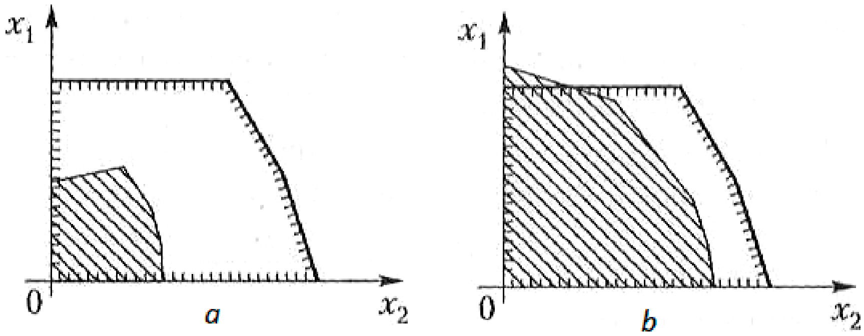

Figure 2. Allowable set of solutions. (**a**) "dirty" technologies; (**b**) "clean" technologies.

The resulting model of the optimisation and control problem (6)–(7) allows us to describe the tasks in the field of macroeconomics, which characterises products on a national or regional scale, allowing the control of the production technology.

For microeconomics at the individual production level, model (6)–(7) will not work, because the manufacturer is interested, firstly, in achieving the highest output, and the question of compliance with environmental standards (8) is secondary, if only because this requirement is not reflected in the objective function. Therefore, in order to take into account the environmental factor in microeconomics, it is necessary to introduce the cost and payment of excess pollution standards into the objective function. Thus, the function of income from production $F(\overline{x})$ is defined as (10): $P = pF(\overline{x}) - \overline{z}\ \overline{\delta}$, which takes into account the aggregated price of the produced products (p), production function ($F(\overline{x})$), costs of eliminating pollution in case of exceeding the relevant standards ($\overline{Z}$) and the vector of "inclusions"—the pollution charges ($\overline{\delta}$), which is determined by Expression (11).

In the model of optimisation and waste management in microeconomics (10), taking into account Conditions (11), (9) and (13), production opportunities due to the matrix of constraint coefficients (A) and the vector of constraints on resources ($\overline{b}$), as well as technological impact standards on the environment and the costs of eliminating the consequences of exceeding them (vectors $\overline{Z}$ and $\overline{w}^*$). To comply with "tough" environmental legislation, the manufacturer will be forced to use more advanced technologies to reduce the specific technogenic waste (matrix coefficients C_p in (4)). In countries with developed economies, as a rule, this model of revenue optimisation is applied taking into account waste management, i.e., the cost of waste disposal.

In the tasks of production management according to environmental and economic criteria, it is usually necessary to maximise the yield of target products, considering the required quality indicators, with limited costs and taking into account environmental requirements. Since there is usually no best solution according to all criteria, a reasonable compromise is needed. Since only a decision-maker can know which indicators are more important, the solution of multicriteria problems of MD should be based on unclear information about the knowledge, experience and preferences of the decision-maker. The information obtained on the basis of the judgements of the decision-maker allows us to identify its preferences regarding the values of the criterion, when comparing the values of various criteria and is very important for choosing an effective solution.

In implementing paragraph 9 of the proposed MM + PO heuristic algorithm for greater validity, dialogue algorithms can be built to adjust the values of the weighting coefficients of the criteria and restrictions: g and (or) b, analyse the obtained decision-makers and select new values. In the process of dialogue with the system, the decision-maker studies the possibilities of obtaining different solutions, their sensitivity to the values of weighting coefficients, thereby having the opportunity to influence the quality of decisions. Such opportunities are achieved through dialogue with the decision maker, increasing their work volume.

Currently, new "green" technologies make it possible to use almost all types of waste on a commercially viable basis. Polymers, including polyethylene wastes, which are a valuable raw material for numerous products, make up more than 20% of waste in Kazakhstan and this is growing rapidly. This requires the need for effective management of these and other wastes, based on the models and methods proposed in this work.

In this work, methods of recycling and waste management based on optimisation and control methods were identified as effective approaches to solving such production issues. Models are proposed to optimise income from production considering environmental standards that relate to the field of macroeconomics and microeconomics.

In contrast to previous approaches, our proposed method sets and solves a fuzzy problem in a fuzzy environment based on the knowledge and experience of the DM and taking into account the membership function of fuzzy parameters, i.e., without converting them to deterministic problems. This heuristic approach allows one to maximize the use of the collected fuzzy information, knowledge, experience, and intuition of specialists and experts, the DM, and to obtain adequate solutions in a fuzzy environment. In the proposed heuristic method, the DM studies the possibilities of obtaining different solutions, their sensitivity to the values of weight coefficients, and influence the quality of the solution by changing the initial data, taking into account its preference and the current production situation. Such opportunities are achieved through dialogue with the DM, thus increasing the volume of work.

6. Conclusions

A complete modernisation of existing technological capacities is required to minimise waste volumes. For this, a quality list to select the best available environmentally friendly technologies is required, which should reflect the advanced technologies used in economically developed countries to reduce emissions of various pollutants into the environment. In several countries, the introduction of the best available technologies has significantly improved the environmental conditions in industrial areas and has become the basis for economic growth and increased competitiveness of enterprises.

In existing models of industrial waste management tasks, the acceptable set is formed by the following two productive balances: $\overline{x} \geq 0$, $\overline{z} \geq 0$ and $A\overline{x}^T \leq \overline{b}^T$, where $\overline{x}$ denotes a vector-string of products produced using the appropriate resources, $\overline{z}$—payments for environmental pollution, A—a matrix consisting the coefficients of resource constraints, and $\overline{b}$—the constraint vector defined by production capabilities [1,5,12]. In contrast to the known models, in the proposed model, the allowed set, in addition to these production ratios, also includes a restriction on "production purity": $\overline{w} \leq \overline{w}^*$, $\overline{w}$—pollutions vector; $\overline{w}^*$—vector of environmental regulations, i.e., permissible waste for each type of pollution. This additional condition $\overline{w} \leq \overline{w}^*$ means that the amount of pollution should not exceed the permissible waste for each type of pollution.

In order to clearly explain the differences and novelty of the results with existing similar results, a comparison table (Table 1) is compiled, where the results obtained using the proposed model and known models using the "MANAGER" software package are entered.

Table 1. Comparison of the results of using the known models and the proposed waste management model in solving the problem of optimizing the waste of the Atyrau refinery's primary processing.

№	Name of the Applied Models	The Optimal Value of the Objective Function $F(x)$	Leftover Available Resources	Accounting the Vector of Environmental Regulations $\overline{w}^*$
1	Existing waste management models [1,5,8,12]	$F(x)$ 3690 thous. tg	0, i.e., resources are fully used	not consider
2	The proposed waste management model, which additionally takes into account the purity of production	$P = pF(\overline{x}) - \overline{z}\,\overline{\delta}$ 3567 thous. tg	0, i.e., resources are fully used	It takes into account, in the form of an additional restriction $\overline{w} \leq \overline{w}^*$ on the permissible waste for each type of pollution.

As can be seen from the table below, the value of the objective function, when solving the problem of optimizing the production of petroleum products with the management of waste and allocated resources, when using existing models compared to the proposed model, is 23 thousand tenge (3690 − 3567 = 23 thousand tenge) more. However, the fact is that when applying the model we offer, we additionally take into account: p—the aggregate price of manufactured products, $\overline{Z}$—payments for environmental pollution, and $\overline{\delta}$—the vector of "inclusions" of payments for pollution. This allows us to take into account the vectors of environmental regulations $\overline{w}^*$, which ensures "production purity".

Since at the present stage of development of society and production, compliance with environmental requirements and cleanliness of production are the main requirements, it is necessary to apply the proposed model when solving problems of optimizing production with waste management. The existing models, although as the example shows, provide a little more revenue (26 thous. tg.), are unprofitable because they do not take into account environmental requirements and can lose much more in the form of fines for pollution, for exceeding permissible waste and violations of environmental regulations $\overline{w}^*$. All these arguments allow us to justify the adequacy and need of the proposed model in solving problems of optimizing real production and waste management.

Thus, in contrast to the existing researches in this work for integrating environmental considerations in microeconomics, a model is proposed in which the transition to value expressions in the objective function $F(\overline{x})$ and payment for exceeding the pollution standards: $P = pF(\overline{x}) - \overline{z}\,\overline{\delta}$, where p denotes aggregate price of products and $\overline{\delta}$ refers to vector "inclusions" of payments for pollution, as determined by the expression:

$$\delta_j = \begin{cases} 0, \ w_j \leq w_j^*, \\ 1, \ w_j > w_j^*. \end{cases} \quad j = \overline{1, m}$$

In well-known approaches to solving fuzzy problems using a set of level α, the original fuzzy problem is reduced to a system of clearly problems. This approach leads to the loss of a significant part of the original fuzzy information, which reduces the adequacy of the solution.

For a more detailed explanation of the main contribution and originality of the work, it can be noted that the proposed model and the developed heuristic method for solving the problem of optimizing production and waste management in the conditions of fuzzy constraints allow us to more adequately describe the real situation in production. This is because the proposed model allows us to consider payments for environmental pollution, and environmental standards, which ensures a clean production. The heuristic method takes into account the experience and knowledge of the person (DM) to more adequately describe the situation in a fuzzy environment and to provide a more efficient solution given the preferences of the decision maker.

We applied the proposed approach to formulate and solve the problem of revenue optimisation and waste management in the production of diesel fuel and petrol at the technical facility of the Atyrau Oil Refinery. The optimal decision to the production optimisation problem was determined using the MANAGER software package. Then, with the help of additional calculations, the final solution to the problem of optimising production with waste management, i.e., including payments for pollution and waste, was obtained.

The mathematical formulation of the decision-making problem for waste management in a fuzzy environment was formalised, developing a heuristic algorithm for its solution. The statement of the problem was formulated as a task of FMP, with the proposed heuristic algorithm for solving the obtained fuzzy problem based on the use of decision-making, on the application of the MPC for criteria and the Pareto principle of optimality for constraints, modified to work in a fuzzy environment.

The authors continue research of the proposed model and the heuristic method, and on their application to solve other problems of optimization of production and waste management of chemical and petrochemical technological facilities. In the future, research will be conducted on the development of fuzzy models for optimizing production and waste management under conditions of fuzzy initial information. New heuristic algorithms for solving the problem of production optimization based on the modification of other optimality principles for working in a fuzzy environment will also be proposed, e.g., the principles of the main criterion, ideal point, quasi-equality and lexicographic principle. This allows the DM to choose a more suitable and convenient method for solving the problem, depending on the current situation, on the availability of source data, on the accuracy and speed of the solution, and on other characteristics of the algorithms. Based on these results, it is planned to create an intelligent decision support system that is convenient for operation.

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Abbreviations

DM	Decision-maker
EU	European Union
FMP	Fuzzy mathematical programming
GDP	Gross domestic product
MD	Making decisions
MM	Maximin
MPC	Maximum permissible concentration
PO	Pareto optimality
RK	Republic of Kazakhstan
tg	Tenge

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