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IMPLEMENTATION OF THE GRAVITY SEARCH METHOD FOR OPTIMIZATION BY COST EXPENSES OF PLANS FOR MULTIFACTORIAL EXPERIMENTS

*One of the main ways to improve the efficiency of experimental research is the use of methods for planning experiments. At the same time, experiment planning can significantly reduce the amount of experimental research by reducing the number of experiments, as well as improve the accuracy and reliability of the results obtained. It is characteristic that the experiments in terms of experiment are not equivalent, that is, their implementation requires different material and time costs. In this regard, the problem arises of optimizing the plans of multivariate experiments in terms of cost or time costs. This is especially important when studying valuable and long-term processes. To solve the problems of optimizing plans for multifactorial experiments in terms of cost (time) costs, it is necessary to develop effective methods for finding optimal plans and their software. Existing methods for optimizing experimental plans are characterized by such shortcomings as low speed, a limited number of studied object factors, and the exact solution is not always found. This article explores the method of gravitational search for the optimal cost (time) cost plan for multifactorial experiments. The method uses the analogy of the motion of solid bodies due to their gravitational interaction. In this case, the rows of the experiment planning matrix are considered as such solid bodies, which are placed in it depending on the decrease in the cost of transitions between rows (gravity). An algorithm and software have been developed that implement the proposed method. The program is presented in the algorithmic language Python. On a number of examples for the study of technological processes, the efficiency and effectiveness of the method of gravitational search for optimal cost (time) costs of plans for multifactor experiments has been proved. **The object of the research:** processes of optimization of plans of multifactorial experiments according to cost (time) costs. **The subject of the study:** the method of gravitational search for the optimal cost (time) plans of multifactorial experiments and the software implementing it.*

Keywords: *experiment plan; gravity search; optimization; cost; time; software.*

Introduction

In science and industry, experimental methods of obtaining mathematical models of objects under study are widely used [1-3]. Simultaneously, the desire of researchers to obtain these models with minimal cost and time spent on the experiment is fully justified. The methods of the theory of experiment planning make it possible to make the experimenter's work more focused and organized, reduce the volume of experimental studies, and to increase the accuracy and reliability of the obtained results.

Simultaneously, an important task is the research and analysis of cost and time optimization methods of plans for multifactorial experiments aimed at the search for effective and economic methods.

Object of research: processes of optimization of plans of multifactorial experiments according to cost (time) costs.

The subject of the study: the method of gravitational search for the optimal cost (time) plans of multifactorial experiments and the software implementing it.

The purpose of the research: development of a method of gravitational search for cost- and time-optimized plans for multifactorial experiments, software for its implementation, and evaluation of their effectiveness.

1. Analysis of recent publications

Combinatorial optimization methods can be used to solve optimization problems in terms of the cost (time) costs of plans for multifactorial experiments [4-6]. The following optimization methods can be used to solve them: complete enumeration, permutation analysis, random enumeration, branch and bound method [7–9], and Gray code method [10, 11]. Genetic algorithms are used to optimize both continuous [12–16] and discrete

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objects; ant colony algorithms [21–23] and annealing simulation algorithms [24, 26] are also widely used.

In [7-9], a comparative analysis of such optimization methods in terms of the cost (time) costs of multivariate experiment plans was carried out: permutation analysis (full search), random search, branch, and bound method. Their main disadvantages are low speed, the exact solution is not always found, and you can find only close to the optimal value, a limited number of factors.

The disadvantages of the method based on the use of the Gray code [11] are: proximity; single-criteria optimization; applies only to two-level plans of full and small factorial experiments; the effectiveness of the method decreases with increasing input data (the number of factors or their levels).

The main disadvantages of genetic algorithms [12–16] are their approximation, the use of single-objective optimization, and the need for more memory to store intermediate plans for a multivariate experiment.

To optimize the cost (time) costs of plans for multivariate experiments, it is also advisable to use methods such as particle swarm [17, 18, 28], tabu search [19, 20, 29], ant colony algorithms [21–23], and annealing simulation algorithms [24-26].

The main disadvantages of particle swarm methods [17, 18, 28] and tabu search [19, 20, 29] are the randomness of the search, which can affect the final optimization result.

The disadvantages of ant colony algorithms [21–23] are approximation, single-criteria, and random search, which can significantly affect the final optimization result. The annealing simulation algorithm [24–26] is an approximate one-criterion optimization method in which the rate decreases significantly when the number of factors k>5.

Because of preliminary studies, it was established:

1) for objects with the number of factors k=3, the best cost optimization results were obtained using the following methods: full search, Gray code method, annealing simulation and genetic algorithms;

2) for objects with the number of factors k≥4, the best optimization results were obtained using genetic algorithms, a swarm of particles, annealing simulation;

3) according to the time of solving the problem of optimizing plans for multifactorial experiments, the methods can be arranged as follows: tabu search, particle swarm method, annealing simulation, genetic method.

In this regard, it is advisable to study the method of gravitational search for the optimal plan of multifactorial experiments in terms of the cost (time) costs evaluate its performance, efficiency and compare with existing methods.

2. Gravity search method optimal design of the experiment

When applying the method, the initial plan of a multifactorial experiment is given by the matrix X_{pe}.

$$X_{pe} = \begin{vmatrix} X_1^1 & X_2^1 & \dots & X_i^1 & \dots & X_k^1 \\ X_1^2 & X_2^2 & \dots & X_i^2 & \dots & X_k^2 \\ \dots & \dots & \dots & \dots & \dots & \dots \\ X_1^j & X_2^j & \dots & X_i^j & \dots & X_k^j \\ \dots & \dots & \dots & \dots & \dots & \dots \\ X_1^N & X_2^N & \dots & X_i^N & \dots & X_k^N \end{vmatrix}, \qquad (1)$$

the values of the transitions of the factor levels are given by the matrix S_{per}, and the duration by the matrix t_{per}.

$$S_{per} = \begin{vmatrix} S^1_{(+1)(-1)} & S^1_{(-1)(+1)} \\ S^2_{(+1)(-1)} & S^2_{(-1)(+1)} \\ \dots\dots\dots & \dots\dots\dots \\ S^i_{(+1)(-1)} & S^i_{(-1)(+1)} \\ \dots\dots\dots & \dots\dots\dots \\ S^k_{(+1)(-1)} & S^k_{(-1)(+1)} \end{vmatrix},$$

$$t_{per} = \begin{vmatrix} t^1_{(+1)(-1)} & t^1_{(-1)(+1)} \\ t^2_{(+1)(-1)} & t^2_{(-1)(+1)} \\ \dots\dots\dots & \dots\dots\dots \\ t^i_{(+1)(-1)} & t^i_{(-1)(+1)} \\ \dots\dots\dots & \dots\dots\dots \\ t^k_{(+1)(-1)} & t^k_{(-1)(+1)} \end{vmatrix}, \qquad (2)$$

where X_i^j – the value i-th factor studied the process in the j- th experiment;

k – the number of factors of the object of study;

N – the number of experiments in the experiment planning matrix;

$S^i_{(+1)(-1)}$, $S^i_{(-1)(+1)}$ – the value the cost of level transitions for the i-th factor;

$t^i_{(+1)(-1)}$, $t^i_{(-1)(+1)}$ – the value the durations of level transitions for the i-th factor.

It is necessary to find the optimal or close to the optimal plan of experiment X_{opt}, for which the total cost or time of the experiment is minimal, i.e.

$$S_0 = \sum_{j=2}^{N}\sum_{i=1}^{k} S_{i,j} \to \min ,$$
$$t_0 = \sum_{j=2}^{N}\sum_{i=1}^{k} t_{i,j} \to \min , \quad (3)$$

where $S_{i,j}$ – the cost installing the i-th factor in the j-th experiment;

$t_{i,j}$ – the duration the installation of the i-th factor in the j-th experiment.

The method uses the analogy of the motion solids due to their gravitational interaction. To implement this method in the optimization of the cost (time) expenses of the plan for the multifactorial experiment X_{pe} uses the calculation of the value of the cost (duration) of the permutation rows in the matrix of the planning of the experiment in relation to the first line $(X_1^1\, X_2^1 \ldots X_i^1 \ldots X_k^1)$. The string with the minimum value of the cost (duration) of the transition is set second in the matrix X_{pe}. A similar procedure is performed for the second line, and the found line with the minimum value of the cost (duration) of the transition in relation to it is set to the third in the matrix X_{pe}. A similar procedure is performed until the last line is formed $(X_1^N\, X_2^N \ldots X_i^N \ldots X_k^N)$.

Then (N-1) of the initial plans of the X_{pe} experiment are synthesized, for which the first line of the matrix becomes 2, 3, 4,…, N lines of the initial plan the experiment (1), respectively. For each of the (N-1) plans, the same procedure is performed as for the initial experiment plan (1).

For the obtained N plans of experiments using formula (3), the cost is calculated S_0 or duration t_0 and of the set N of plans there is one for which S_0 or t_0 have a minimum value. The cost is calculated S_{pe} or duration t_{pe} plan of experiment (1), as well as the gain obtained by optimizing the plan for multifactorial experiment, according to the formulas

$$B_s = S_{pe} / S_{opt} ; B_t = t_{pe} / t_{opt} ,$$

where S_{opt} – the cost of implementation of the optimal plan of experiment;

t_{opt} – duration of implementation of the optimal plan of experiment.

3. An algorithm that implements the method of gravitational search for the optimal design of a multifactorial experiment

The essence of the algorithm, which scheme is presented in Fig. 1, is as follows:

Stage 1. Generation of the initial (initial) matrix of the plan of the full factorial experiment (depending on the number of factors).

Stage 2. Entering the cost matrix of transitions between levels of the planning matrix for each of the factors.

Stage 3. Determination of the cost of implementing the initial matrix of experiment planning.

Stage 4. The calculation of values of transition values between the first row and all subsequent rows of the matrix. Establishing the current line with the minimum cost of implementation. Calculation of the values of the transitions between the set row and the remaining rows of the matrix. We perform until we reach the last line.

Stage 5. Reconstruction of the experimental planning matrix and determination of the minimum cost of its implementation.

Stage 6. In the output matrix, the first row is replaced by the second, and steps 4 and 5 are performed. Then, in the output matrix, the first row is replaced by the third, and so on.

Stage 7. A comparison of the cost of the initial plan of the experiment with the obtained values and determination of the optimal plan.

Stage 8. The calculation of the gain in the cost of implementing the optimal plan for the experiment.

The software implementation of the algorithm is performed using the interpreted and high-level Python language. The distinguishing features of the language are cross-platform, dynamic typing, automatic memory management, introspection, and high-level data structures [27].

Running the program produces main.py. Calculations are performed using the algorithm_1.py module located in the calculated directory. All results of the method operation are stored in the results directory in *.csv files. The structure of the program that implements the proposed method is shown in Fig. 2.

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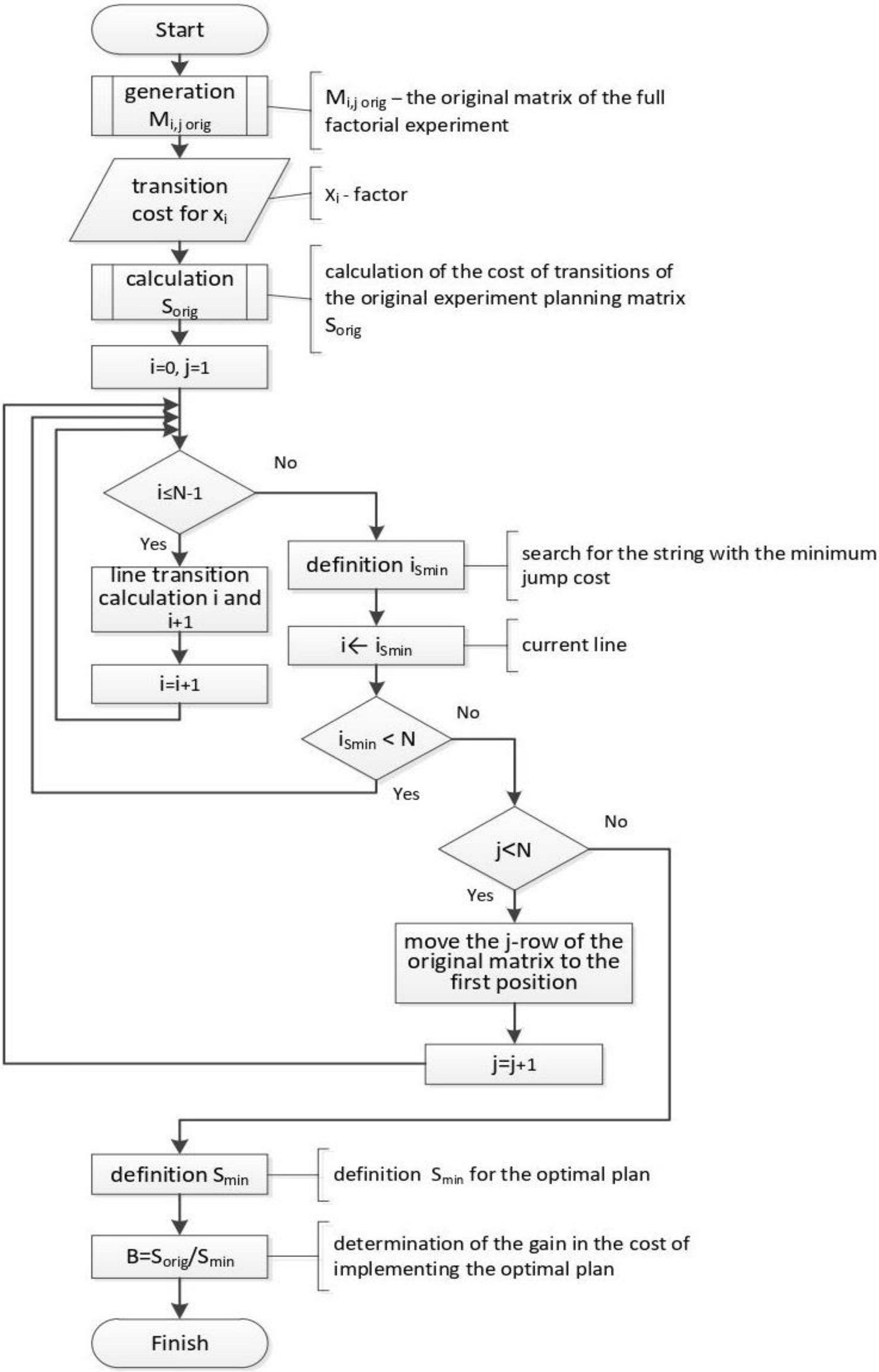

Fig. 1. Scheme of the gravitational search algorithm

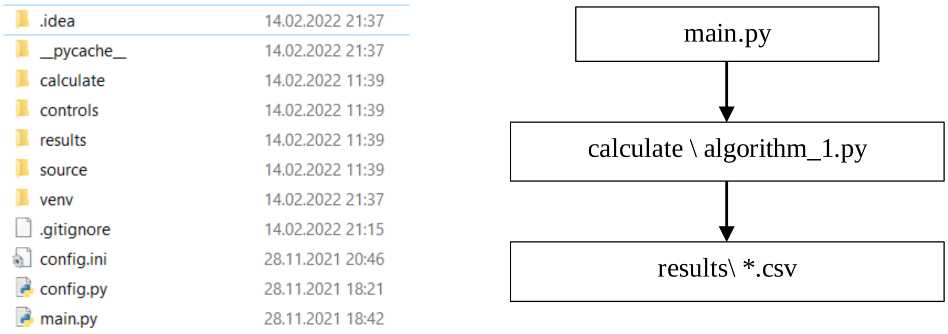

Fig. 2. The structure of the program that implements the proposed method

4. Results of optimizing plans for multivariate experiments

The performance and effectiveness of the gravity method and the software implementing it were evaluated on the basis of multifactorial experiments for the study of the following technological processes: measurement of the area of metallization of printed circuit boards; ultrasonic cutting of silicon wafers on a crystal in the process of manufacturing semiconductor diodes; electroplating of printed circuit boards; and calibration of portable dielcometric moisture meters. Simultaneously, experimental plans were previously obtained for the study of these processes using the methods of analysis of permutations and random search [7, 8]. To study the process of galvanic copper plating of printed circuit boards, a plan of a multivariate experiment was also previously obtained using a genetic algorithm [13], and for the process of calibrating portable dielcometric moisture meters, plans were obtained using the methods swarm of particles and tabu search [30].

To study the technological process measuring the area of metallization of printed circuit boards in the plan for multifactorial experiment, the following factors were introduced: X_1 – the period of time τ from the moment of immersion of the plate in the bath to the moment of registration of voltmeter readings; X_2 – load resistance; X_3 – acidity pH of the electrolyte; X_4 – temperature T of the electrolyte.

The cost of changes in the values the levels of factors from "-1" to "+1" and from "+1" to "-1" are shown in Table 1.

The cost implementing the experiment under this plan was 2.97 conventional units, whereas the cost of the initial plan was 9.7 conventional units. Thus, we have a gain in the cost of the experiment to implement the process measurement of the area of metallization-printed circuit boards in 3.26 times. The optimal cost of the experimental plan is shown in Table 2.

Table 1

Cost of changes in the values of factor levels

Factor	The cost of changes in the values of levels, conventional units	
	«-1» to «+1»	«+1» to «-1»
X_1	0.49	0.33
X_2	0.06	0.06
X_3	0.95	0.97
X_4	0.16	0.20

Table 2

The optimal plan of experiment

Experiment number	Factors			
	X_1	X_2	X_3	X_4
1	-1	+1	-1	-1
2	-1	-1	-1	-1
3	-1	-1	-1	+1
4	-1	+1	-1	+1
5	+1	+1	-1	+1
6	+1	-1	-1	+1
7	+1	-1	-1	-1
8	+1	+1	-1	-1
9	+1	+1	+1	-1
10	+1	-1	+1	-1
11	+1	-1	+1	+1
12	+1	+1	+1	+1
13	-1	+1	+1	+1
14	-1	-1	+1	+1
15	-1	-1	+1	-1
16	-1	+1	+1	-1

In study the process of ultrasonic cutting of silicon wafers into crystals in the production of semiconductor diodes, the following factors were selected as factors: X_1 – the initial value of the static load on the cutting tool; X_2 – magnetizing current the magnetostrictor of the ultrasonic generator; X_3 – load switching moment.

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The changes cost in the values of factor levels in the study are shown in Table 3.

Table 3

Cost of changes in the values of factor levels

Factor	The cost of changes in the values of levels, conventional units	
	«-1» to «+1»	«+1» to «-1»
X_1	5	4.5
X_2	2	1.8
X_3	1	0.8

The cost of implementing the experiment under this plan was 11.9 conventional units, whereas the cost of the initial plan was 40.3 conventional units. Thus, we have a gain in the cost of the experiment 3.39 times compared to the original plan. The optimal cost of the experimental plan is shown in Table 4.

Table 4

The optimal plan of experiment

Experiment number	Factors		
	X_1	X_2	X_3
1	+1	+1	-1
2	+1	+1	+1
3	+1	-1	+1
4	+1	-1	-1
5	-1	-1	-1
6	-1	-1	+1
7	-1	+1	+1
8	-1	+1	-1

The following factors have been introduced into the plan multifactorial experiment for the study technological process of galvanic copper plating of printed circuit boards: X_1 – concentration $CuSO_4$ in the electrolyte of the galvanic bath; X_2 – concentration H_2SO_4 in solution; X_3 – current density in the galvanic tub; X_4 – board processing time in the tub.

The changes cost in the values of factor levels in the study are shown in Table 5.

Table 5

Cost of changes in the values of factor levels

Factor	The cost of changes in the values of levels, conventional units	
	«-1» to «+1»	«+1» to «-1»
X_1	18.85	7.45
X_2	8.65	4.45
X_3	0.18	0.18
X_4	1.15	0.77

The cost of the experiment under this plan was 25.83 conventional units, whereas the cost of the initial plan was 252.6 conventional units. Thus, the gain in the cost of the experiment is 9.78 times compared to the original plan. The optimal cost experiment plan is shown in Table 6.

Table 6

The optimal plan of experiment

Experiment number	Factors			
	X_1	X_2	X_3	X_4
1	+1	+1	-1	+1
2	+1	+1	+1	+1
3	+1	+1	+1	-1
4	+1	+1	-1	-1
5	+1	-1	-1	-1
6	+1	-1	+1	-1
7	+1	-1	+1	+1
8	+1	-1	-1	+1
9	-1	-1	-1	+1
10	-1	-1	+1	+1
11	-1	-1	+1	-1
12	-1	-1	-1	-1
13	-1	+1	-1	-1
14	-1	+1	+1	-1
15	-1	+1	+1	+1
16	-1	+1	-1	+1

The comparing results the efficiency of the gravitational method with other methods optimizing the plans for multifactorial experiments [30] are shown in Table 7.

Table 7

Results comparison efficiency the methods of optimization the plans of multifactorial experiments

Search method	S_{opt}, conventional units
Gravitational search	25.83
Analysis of reshuffles	30.46
Random search	41.8
Genetic algorithm	25.83

The comparison results of the optimizing methods plans for multifactorial experiments, which are shown in Table 7, show that the cost of implementing the plan obtained by the gravity method is lower than the cost of plans optimized by random search and analysis of permutations, and coincides with the cost of the plan obtained by the genetic algorithm.

To study the calibration process of portable dielcometric moisture meters, the following factors were introduced into the plan for the multifactorial experiment: X_1 – relative dielectric constant of dehydrated petroleum product; X_2 – water content.

The changes cost in the values of factor levels in the study are shown in Table 8.

Table 8

Cost of changes in the values of factor levels

Factor	The cost of changes in the values of levels, conventional units	
	«-1» to «+1»	«+1» to «-1»
X_1	10	10
X_2	20	60

The cost of the experiment under this plan was 40 conventional units, whereas the cost of the initial plan was 50 conventional units. Thus, the gain in the cost of the experiment is 1.25 times compared to the original plan. The optimal cost the experiment plan is shown in Table 9.

Table 9

The optimal plan of experiment

Experiment number	Factors	
	X_1	X_2
1	+1	-1
2	-1	-1
3	-1	+1
4	+1	+1

The comparing results the efficiency of the gravity method with other methods of optimizing the plans for multifactorial experiments [30] are shown in Table 10.

Table 10

Results comparison efficiency the methods of optimization the plans of multifactorial experiments

Search method	S_{opt}, conventional units
Gravitational search	40
Permutation analysis	54
Tabu search	50
A swarm of particles	48
Random search	56

The comparison results of methods optimizing plans for multifactorial experiments, which are given in Table 10, show that the cost of the plan obtained by the gravity method is lower than the cost of plans optimized by random search, permutation analysis, tabu search, and swarm of particles. Thus, the given examples of the implementation of the gravitational search method for cost-loss optimization, the plans for multifactorial experiments confirm the effectiveness of its use.

Conclusions

This article proposes a gravitational method for finding cost-optimal (time costs) plans for multifactorial experiments. Software in the Python algorithmic language has been developed to implement this method. Several examples of technological processes show the efficiency and effectiveness of the proposed gravitational method.

Simultaneously, it was established that the cost of implementing plans obtained by the gravity method is lower than the cost of plans optimized by random search and analysis of permutations, tabu search, swarm of particles and coincides with the cost of plans obtained by genetic algorithm.

The scientific novelty is that the proposed method of synthesis of the optimal or close to optimal cost (time costs) expenses of plans for multifactorial experiments, which differs from existing ones in that it is based on the use of gravitational search, which allows for building such experimental plans without full search for options for the permutation of experiments and reduces the cost (time costs) expenses of their implementation in comparison with existing methods.

The practical significance of the developed software lies in the possibility of applying the gravitational method for the two-parameter optimization of compositional plans for multifactorial experiments.

Contributions of authors: formulation of the purpose and statement of a research problem, development of conceptual provisions of research – **Nikolay Koshevoy;** selection and use of the software and hardware for modeling and presentation results – **Iryna Ilina;** review and analysis of information sources, formulation of conclusions **– Volodymyr Tokariev;** method development and analysis of research results – **Anna Malkova**; processing of research results – **Victor Muratov.**

All the authors have read and agreed to the published version of the manuscript.

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РЕАЛІЗАЦІЯ МЕТОДУ ГРАВІТАЦІЙНОГО ПОШУКУ ДЛЯ ОПТИМІЗАЦІЇ ЗА ВАРТІСНИМИ ВИТРАТАМИ ПЛАНІВ БАГАТОФАКТОРНИХ ЕКСПЕРИМЕНТІВ

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Одним із основних шляхів підвищення ефективності експериментальних досліджень є застосування методів планування експериментів. При цьому планування експерименту дозволяє значно скоротити обсяг експериментальних досліджень за рахунок зменшення числа дослідів, а також підвищити точність і надійність отриманих результатів. Характерно, що досліди в плані експерименту не є рівноцінними, тобто для їх реалізації необхідні різні матеріальні та часові витрати. У зв’язку з цим виникає задача оптимізації планів багатофакторних експериментів за вартісними або часовими витратами. Це особливо важливо при дослідженні коштовних і тривалих процесів. Для рішення задач оптимізації планів багатофакторних експериментів за вартісними (часовими) витратами необхідна розробка ефективних методів пошуку оптимальних планів та програмного забезпечення, що їх реалізує. Для існуючих методів оптимізації планів експериментів характерні такі недоліки, як низька швидкодія, обмежена кількість факторів об’єкта, що досліджується, не завжди знаходиться точне рішення. В даній статті досліджується метод гравітаційного пошуку оптимального за вартісними (часовими) витратами плану багатофакторних експериментів. У методі використовується аналогія руху твердих тіл внаслідок їх гравітаційної взаємодії. При цьому в якості таких твердих тіл розглядаються рядки матриці планування експерименту, які розміщуються в ній в залежності від зменшення вартості переходів між рядками (сила тяжіння). Розроблені алгоритм та програмне забезпечення, які реалізують запропонований метод. Програма представлена на алгоритмічній мові Python. На ряді прикладів для дослідження технологічних процесів доведена працездатність та ефективність методу гравітаційного пошуку оптимальних за вартісними (часовими) витратами планів багатофакторних експериментів. **Об’єкт дослідження:** процеси оптимізації планів багатофакторних експериментів за вартісними (часовими) витратами. **Предмет дослідження:** метод гравітаційного пошуку оптимальних за

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вартісними (часовими) витратами планів багатофакторних експериментів та програмне забезпечення, що його реалізує.

Ключові слова: план експерименту; гравітаційний пошук; оптимізація; вартість; час; програмне забезпечення.

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