

APPLICATION OF THE “JUMPING FROGS” ALGORITHM FOR RESEARCH AND OPTIMIZATION OF THE TECHNOLOGICAL PROCESS

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ABSTRACT

Context. An application of the method of a “jumping frogs” search algorithm to construct optimal experiment plans for cost (time) in the study of technological processes and systems that allow the implementation of an active experiment on them is proposed.

The object of study are optimization methods for cost (time) costs of experimental designs, based on the application of a “jumping frogs” search algorithm.

Objective. To obtain optimization results by optimizing the search of a “jumping frogs” search algorithm for the cost (time) costs of plans for a full factorial experiment.

Method. A method is proposed for constructing a cost-effective (time) implementation of an experiment planning matrix using algorithms for searching for “jumping frogs”. At the beginning, the number of factors and the cost of transitions for each factor level are entered. Then, taking into account the entered data, the initial experiment planning matrix is formed. Then, taking into account the entered data, the initial matrix of experiment planning is formed. The “jumping frogs” method determines the “successful frog” by the lowest cost of transitions between levels for each of the factors. After that, the permutations of the “frogs” are performed. The “frog” strives for the most “successful” and, provided it stays close, remains in the location. Then the gain is calculated in comparison with the initial cost (time) of the experiment.

Results. Software has been developed that implements the proposed method, which was used to conduct computational experiments to study the properties of these methods in the study of technological processes and systems that allow the implementation of an active experiment on them. The experimental designs that are optimal in terms of cost (time) are obtained, and the winnings in the optimization results are compared with the initial cost of the experiment. A comparative analysis of optimization methods for the cost (time) costs of plans for a full factorial experiment is carried out.

Conclusions. The conducted experiments confirmed the operability of the proposed method and the software that implements it, and also allows us to recommend it for practical use in constructing optimal experiment planning matrices.

KEYWORDS: optimal plan, jumping frogs search algorithm, optimization, experiment planning, cost, win.

ABBREVIATIONS

MSRF is a mixed solid rocket fuel;

SRF is a solid rocket fuel.

t_i is a time of the i -th factor of the studied process;

b_{ij} is an unknown coefficients of the mathematical model;

Y_i is a process optimization criteria.

NOMENCLATURE

k is a number of object factors introduced into the study;

t is a program run time, s;

B is a winnings;

N is a number of experiments in the planning matrix of the experiment and the matrix of costs of transitions between the levels of factors;

X_j is a levels of factors;

C_0 is a total cost of the experiment, conv. units;

t_0 is a total time of the experiment, h;

$C_{i,j}$ is a cost of the transition from the i -th experience to the j -th, conventional units;

$t_{i,j}$ is a time of the transition from the i -th experience to the j -th, conventional units;

C_i is a cost of the i -th factor of the studied process;

INTRODUCTION

The most important part of scientific studies are experiments. This is one of the main ways to get new scientific knowledge. The basis of this method is an experiment, representing a scientifically delivered experience or observation of the phenomenon under precisely taken into account conditions, allowing to monitor its progress, to control it, to recreate it every time when these conditions are repeated. From ordinary, passive observation, the experiment is distinguished by the active influence of the researcher on the phenomenon being studied.

Planning an experiment is a section of mathematical statistics that studies methods for organizing a set of experiments with different conditions to obtain the most reliable information about the properties of the object under investigation in the presence of uncontrolled random perturbations. The use of experimental planning makes the experimenter's behavior purposeful and organized, significantly contributing to the increase of his labor productivity and the reliability of the results obtained. An important advantage of the method is its universality, suitability in the vast majority of areas of research.

The object of study is the technological processes and systems that allow the implementation of an active experiment on them.

The subject of study is the optimization method for cost (time) costs of experiment plans, based on the application of a "jumping frogs" search algorithm.

The purpose of the work is the development of a method and software for optimization of plans for a full factorial experiment using the search algorithm for "jumping frogs".

1 PROBLEM STATEMENT

Experimental research methods are widely used to optimize production processes. One of the main objectives of the experiment is to obtain the maximum amount of information about the influence of the factors studied on the production process. Further, a mathematical model of the object under investigation is constructed. At the same time, it is necessary to obtain models with minimal cost and time costs. This is especially important in the study of long and costly processes. The task of optimizing plans at a cost (time) of the experiment is NP-complete, i.e. for its solution takes time and a large number of computations, rapidly growing with increasing dimension of the problem. Therefore, a complete search of all possible solutions is difficult. In this connection it is necessary to find solutions using approximate algorithms.

The task of optimizing the design of experiments on cost costs is NP-complete, i.e. for its solution, it takes time and a large number of calculations, rapidly growing with increasing dimension of the problem. Therefore, a complete enumeration of all possible solutions is difficult. In this regard, it is necessary to find solutions using approximate algorithms, for example, such as an algorithm of optimization by a swarm of particles.

1. Total cost of the experiment:

$$C_0 = \sum_{i=1}^k C_i + \sum_{j=1}^N \sum_{i=1}^k C_{ij} \rightarrow \min .$$

2. Total experiment time:

$$t_0 = \sum_{i=1}^k t_i + \sum_{j=1}^N \sum_{i=1}^k t_{ij} \rightarrow \min .$$

2 REVIEW OF THE LITERATURE

Combinatorial optimization methods are known [3–8], but they are not used for constructing multivariate experiment plans that are optimal in cost and time costs. There are also known examples of constructing multi-factorial design of an experiment described in, based on the use of the following optimization methods: analysis of permutations; sequential approximation method; branch and bound method; random search (permutation of rows of the planning matrix); simplex method; ant algorithm; genetic algorithm; annealing method; greedy algorithm; swarm of particles; jumping frogs [12]; monkey search [13]; search for a school of fish [16].

The effectiveness of the use of these methods is shown in the study of various technological processes, devices and systems. These methods have both advantages and disadvantages. For example, with a large number of factors, a complete search of all the rows of the experiment planning matrix requires a considerable length of time, while other methods make it possible to obtain an optimal experiment design for a limited number of factors k . With a large number of factors, the optimization results only approach the optimal experimental design. To solve the problem of constructing optimal experimental designs, it is advisable to use the "jumping frogs" method developed by the authors to compare optimization results. Based on this method, the technological process of manufacturing SRF was investigated and optimized.

All these methods have both advantages and disadvantages. For example, with a large number of factors, a lot of time is required for a complete search of all the rows of the planning matrix, and other algorithms allow obtaining an optimal experiment plan for a limited number of factors k . With a large number of factors, the optimization results are approximated to the optimal experiment plan. In view of this, it is advisable to use the search algorithm for "jumping frogs" by a school to compare the results. Optimization of experiment cost plans full (time) costs by exhaustive search at the current level of computing techniques can only be solved for the number of factors $k \leq 3$. Therefore, the problem of reduction many plans for a multivariate experiment with minimum number of transitions of factor levels to search for the optimal cost (time) the cost of its implementation.

There are methods based on the determination of the content of liquid-viscous components, the effect of products on the physicochemical properties of MSRF [3]. In well-known sources [4], mathematical models of the influence of the fractional composition of the SRF on the characteristics of MSRF are not given explicitly.

3 MATERIALS AND METHODS

A method and software for optimizing the plans for a full factorial experiment on cost (time) costs using the search algorithm for a "jumping frogs" has been developed. The essence of the application of the search algorithm for "jumping frogs" is as follows:

Step 1. At the beginning of the work, the number of factors k is introduced.

Step 2. Enter the cost of transitions between levels for each of the factors.

Step 3. Depending on the selected number of factors, an experiment planning matrix is constructed.

Step 4. Calculation of the initial cost of the experiment.

Step 5. Generation of the cost matrix of transitions between levels for each of the factors.

Step 6. Sorting the indices and generating an array of indices for the cost of transitions between levels for each of the factors.

Step 7. Rearrangements in the columns in accordance with the array of indices for the cost of transitions between levels for each of the factors.

Step 8. Enumerating between all blocks of columns (“memplexes” in which the “frog” moves).

Step 9. Determining the starting point for further enumeration, based on the least sum of the cost of transitions between levels for each of the factors.

Step 10. Performing a search within the column block in which the “frog” is located by the minimum value of the sum of the costs of transitions between levels for each of the factors.

Step 11. Go to the next row of the planning matrix and compare with the previous one. A search is performed in the column block with the lowest value of the sum of the costs of transitions between levels and the establishment of the corresponding block (interchanging in the planning matrix of the experiment).

Step 12. Construction of an optimal experiment planning matrix.

Step 13. Calculation of the total cost of the experiment.

Step 14. The calculation of the magnitude of the gain B as the ratio of the initial cost of the C_{init} experiment to the cost of implementing the optimal planning matrix of the experiment C_{opt} .

$$B = \frac{C_{\text{init}}}{C_{\text{opt}}}$$

Step 15. Calculation of the time t spent on optimizing the design of the full factorial experiment using the “jumping frogs” method.

4 EXPERIMENTS

Practical experiments implemented in this article were carried out as part of the study of the technological process of manufacturing solid rocket fuel (hereinafter referred as SRF). Existing types of mixed solid rocket fuel (hereinafter referred as MSRF) have a specific impulse of ≤ 250 s, with an average pressure in the combustion chamber $p_k = 70\text{--}100$ atm. and the degree of expansion of the nozzle (the ratio of the nozzle exit cross-sectional area to the critical nozzle cross-sectional area, hereinafter referred to as S_a/S_{kr}) $S_a/S_{kr} \leq 10$, however, the

modern space-rocket industry requires the creation of MSRF recipes with an increased impulse of ≥ 265 s.

The work presented in this article was performed to optimize the formulation with a thermodynamic estimation of parameters, which consists in finding the optimal formulation of solid rocket fuel with optimization criteria: specific impulse, fuel density.

The following components were used to model the formulation: product 28, aluminium powder A-4, product 14 and binders based on modified rubber of the type with technological additives. The use of such substances in the manufacture of SRF allows you to create formulations with a high level of energy and acceptable performance characteristics at the stages of manufacturing SRF, product operation, etc. It is also necessary to measure the pressure in the combustion chamber of the engine.

The binder content is taken in the amount of 11%, since the results of laboratory studies have shown that such a quantity of binder is necessary to achieve the required rheological characteristics of the mixture in the manufacture of SRF. However, the use of modern substances in the manufacture of binders for SRF allows to increase the degree of filling of SRF with solid substances, due to a decrease in the content of liquid-viscous components to 10% \rightarrow 9% \rightarrow 8%, which theoretically allows us to expect an increase in specific impulse by 1% \rightarrow 2% \rightarrow 3%. In this case, it is necessary to monitor performance at an acceptable level. Since the basic formulation has a relatively low oxygen balance, an equivalent increase in the degree of SRF filling with solids, due to a decrease in liquid-viscous components, should be performed in favor of an oxidizing agent (product 28).

We take energy components in such quantity:

- product 28 – 35% – 70%;
- aluminum A-4 – 9% – 44%;
- product 14 – 10% – 45%.

The range of variation of energy components is 35%, which is necessary for the formation of experimental plans and allows you to cover a wide range of SRF recipes. The approach used to optimize the prescription composition of SRF is based on the construction of optimal experimental plans and allows one to determine with high accuracy the optimal composition of SRF according to optimization criteria.

The experimental design was optimized using this method. A full factorial experiment was conducted to study the formulation with thermodynamic evaluation of the parameters, on the basis of which recommendations were made regarding the influence of the formulation on the energy characteristics of the rocket engine and component content. Mathematical models are constructed, the coefficients of which characterize the influence of the recipe content on acceptable operational characteristics at the stages of manufacturing SRF.

We determine the factors by which it is possible to act on the optimized object. The choice of factors is a very crucial step in preparing for the planning of an experiment, the success of optimization depends on

their successful choice. Factors affecting the energy characteristics of the MSRF were selected: X_1 is the content of the product 28 component; X_2 is the content of the aluminium component A-4; X_3 is the content of component product 14.

The polynomial model of the process under study, which we will use at the first stage of the planning of the experiment, is an incomplete quadratic function:

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_{12}X_1X_2 + b_{13}X_1X_3 + b_{23}X_2X_3 + b_{123}X_1X_2X_3,$$

where $b_0, b_1, b_2, b_{12}, b_{13}, b_{23}, b_{123}$ are the unknown coefficients of the mathematical model.

The first stage of planning an experiment to obtain a mathematical model is based on varying factors at two levels: “+1” – the upper limit of the range of component content; “-1” is the lower limit of the range of component content. The process optimization criteria are as follows: Y_1 – specific impulse, s; Y_2 – density, kg/m³. Based on the results of the experiment, we will find the values of the unknown coefficients of the model and the optimal ratios of the components. The planning matrix of the initial experiment is given in table 1.

Table 1 – Initial experiment planning matrix

Experience number	Destination of 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 costs of changing the values of factor levels in the study of energy components by specific impulse are given in table 2. The natural values of the levels of factors in the study of energy components depending on the content of the binder components are given in table 3. The cost of changing the values of factor levels in the study of energy components by fuel density are given in table 4.

Table 2 – Costs of changing factor level values in the study of energy components by specific impulse

Cost of changing values of factor levels, conv. units	Designation of factors											
	The content of the binder components 11%			The content of the binder components 10%			The content of the binder components 9%			The content of the binder components 9%		
	X_1	X_2	X_3	X_1	X_2	X_3	X_1	X_2	X_3	X_1	X_2	X_3
from “-1” to “+1”	15.8	10.5	11.5	16.5	10.5	11.5	16.8	10.5	11.5	17.2	10.5	11.5
from “+1” to “-1”	27.0	32.5	33.5	27.4	32.5	33.5	28.0	32.5	33.5	33.6	32.5	33.5

Table 3 – Natural values of factor levels in the study of energy components

Factor levels	Destination of factors		
	The content of the binder components 11%		
	X_1	X_2	X_3
Product 28, %	Aluminium A-4, %	Product 14, %	
“-1”	35	9	10
+1”	70	44	45
Factor levels	Destination of factors		
	The content of the binder components 10 %		
	X_1	X_2	X_3
Product 28, %	Aluminium A-4, %	Product 14, %	
“-1”	36	9	10
+1”	71	44	45
Factor levels	Destination of factors		
	The content of the binder components 9 %		
	X_1	X_2	X_3
Product 28, %	Aluminium A-4, %	Product 14, %	
“-1”	37	9	10
+1”	72	44	45
Factor levels	Destination of factors		
	The content of the binder components 8 %		
	X_1	X_2	X_3
Product 28, %	Aluminium A-4, %	Product 14, %	
“-1”	38	9	10
+1”	73	44	45

Table 4 – Costs of changing factor level values in the study of energy components by fuel density

Cost of changing values of factor levels, conv. units	Designation of factors											
	The content of the binder components 11%			The content of the binder components 10%			The content of the binder components 9%			The content of the binder components 9%		
	X_1	X_2	X_3	X_1	X_2	X_3	X_1	X_2	X_3	X_1	X_2	X_3
from “-1” to +1”	13.8	9.5	10.5	14.5	9.5	10.5	14.8	9.5	10.5	15.2	9.5	10.5
from “+1” to “-1”	25.5	31.5	32.0	24.8	31.5	32.0	26.0	31.5	32.0	31.5	31.5	32.0

5 RESULTS

A method and a program have been developed optimization of plans for a full factorial experiment using the search algorithm for a “jumping frogs”. Their operability and efficiency on some examples of research of systems and technological processes are proved.

The search for the optimal or close to the optimal plan obtained by this method is realized in a short time of the account. It is shown that in order to optimize the plans for a full factorial experiment, it is expedient to use the method of searching for a “jumping frogs” by research in objects with the number of factors $2 \leq k \leq 4$.

The optimal experimental design and research results are given in tables 5–8.

The optimal experimental design and research results for the content of the binder components of 11% are presented in table 5.

For the costs of changing factor levels in the study of energy characteristics by specific impulse, presented in table 2, the optimization results are shown in table 5. The initial cost of the experiment is 515 conv. units The gain and cost of implementing the optimal experimental design obtained as a result of optimization using the “jumping frogs” method are shown in table 10.

Table 5 – Optimal experimental design and research results (binder content 11%)

Specific impulse					Density				
Experi- ence number	Designation of factors			Y ₁	Experi- ence number	Designation of factors			Y ₂
	X ₁	X ₂	X ₃			X ₁	X ₂	X ₃	
1	+1	-1	-1	260.65	1	+1	-1	-1	1.76
2	+1	-1	+1	218.03	2	-1	+1	-1	1.94
3	+1	+1	+1	260.73	3	+1	+1	-1	1.70
4	+1	+1	-1	257.66	4	-1	-1	+1	1.85
5	-1	+1	-1	261.37	5	+1	-1	+1	1.73
6	-1	+1	+1	249.26	6	-1	+1	+1	1.81
7	-1	-1	+1	264.68	7	-1	-1	-1	1.80
8	-1	-1	-1	261.20	8	+1	+1	+1	1.75

The optimal experimental design and research results for the content of binding components of 10% are presented in table 6.

For the costs of changing factor levels in the study of energy characteristics by specific impulse, presented in table 2, the optimization results are shown in table 6. The initial cost of the experiment is 548 conv. units The gain and cost of implementing the optimal experimental design obtained as a result of optimization using the “jumping frogs” method are shown in table 10.

Table 6 – Optimal experimental design and research results (binder content 10%)

Specific impulse					Density				
Experi- ence number	Designation of factors			Y ₁	Experi- ence number	Designation of factors			Y ₂
	X ₁	X ₂	X ₃			X ₁	X ₂	X ₃	
1	-1	+1	-1	267.88	1	-1	+1	-1	1.79
2	-1	+1	+1	225.87	2	+1	-1	-1	1.93
3	+1	+1	+1	268.34	3	+1	+1	-1	1.83
4	+1	+1	-1	267.44	4	-1	-1	+1	1.77
5	+1	-1	-1	268.84	5	-1	+1	+1	1.72
6	+1	-1	+1	258.84	6	+1	-1	+1	1.91
7	-1	-1	+1	271.85	7	-1	-1	-1	1.76
8	-1	-1	-1	268.57	8	+1	+1	+1	1.72

The optimal experimental design and research results for the content of the binder components of 9% are presented in table 7.

For the costs of changing factor levels in the study of energy characteristics by specific impulse, presented in table 2, the optimization results are shown in table 7. In this case, the initial cost of the experiment is 570 conv. units The gain and cost of implementing the optimal experimental design obtained as a result of optimization using the “jumping frogs” method are shown in table 10.

The optimal experimental design and research results for the content of the binder components of 8% are presented in table 8.

Table 7 – Optimal experimental design and research results (binder content 9%)

Specific impulse					Density				
Experi- ence number	Designation of factors			Y ₁	Experi- ence number	Designation of factors			Y ₂
	X ₁	X ₂	X ₃			X ₁	X ₂	X ₃	
1	-1	-1	+1	268.14	1	-1	-1	+1	1.72
2	+1	-1	+1	227.63	2	-1	+1	-1	1.93
3	+1	+1	+1	269.99	3	-1	+1	+1	1.75
4	-1	+1	+1	269.22	4	+1	-1	-1	1.73
5	-1	+1	-1	269.89	5	+1	-1	+1	1.72
6	+1	+1	-1	262.12	6	+1	+1	-1	1.73
7	+1	-1	-1	271.83	7	-1	-1	-1	1.76
8	-1	-1	-1	269.26	8	+1	+1	+1	1.72

For the costs of changing factor levels in the study of energy characteristics by specific impulse, presented in table 2, the optimization results are shown in table 8. In this case, the initial cost of the experiment is 610 conv. units. The gain and cost of implementing the optimal experimental design obtained as a result of optimization using the “jumping frogs” method are shown in table 10.

Table 8 – Optimal experimental design and research results (binder content 8%)

Specific impulse					Density				
Experi- ence number	Designation of factors			Y ₁	Experi- ence number	Designation of factors			Y ₂
	X ₁	X ₂	X ₃			X ₁	X ₂	X ₃	
1	-1	+1	-1	267.90	1	+1	-1	-1	1.72
2	-1	+1	+1	228.75	2	-1	-1	+1	1.93
3	+1	+1	+1	271.45	3	+1	-1	+1	1.75
4	+1	+1	-1	269.71	4	-1	+1	-1	1.75
5	+1	-1	-1	270.64	5	+1	+1	-1	1.76
6	+1	-1	+1	265.79	6	-1	+1	+1	1.70
7	-1	-1	+1	271.50	7	-1	-1	-1	1.75
8	-1	-1	-1	269.58	8	+1	+1	+1	1.73

The experiments carried out confirmed the efficiency of the “jumping frogs” method. The coefficients of mathematical models and the optimal ratio of components are given in table 9. They indicate the influence of factors on optimization criteria.

6 DISCUSSION

When studying the energy characteristics of fuel density, the cost of changing factor levels is presented in table 4, and the obtained optimization results are shown in table 5. The initial cost of the experiment is 475 conv. units The gain and cost of implementing the optimal experimental design obtained as a result of optimization using the “jumping frogs” method are shown in table 10.

When studying the energy characteristics of fuel density, the cost of changing factor levels is presented in table 4, and the obtained optimization results are shown in table 6. The initial cost of the experiment is 500 conv. units The gain and cost of implementing the optimal experimental design obtained as a result of optimization using the “jumping frogs” method are shown in table 10.

When studying the energy characteristics of fuel density, the cost of changing factor levels is presented in table 4, and the obtained optimization results are shown in table 7. The initial cost of the experiment is 526 conv. units. The gain and cost of implementing the optimal experimental design obtained as a result of optimization using the “jumping frogs” method are shown in table 10.

When studying the energy characteristics of fuel density, the cost of changing factor levels is presented in table 4, and the obtained optimization results are shown in table 8. The initial cost of the experiment is 552 conv. units. The gain and cost of implementing the optimal experimental design obtained as a result of optimization using the “jumping frogs” method are shown in table 10.

Table 9 – Mathematical models and optimal component ratios

Criterion optimization	Mathematical model coefficients	Optimal ratios components
The content of the binder components 11%		
Specific impulse	$b_0 = 90.625; b_1 = 13.125;$ $b_2 = 8.125; b_3 = -0.125;$ $b_{12} = 7.375; b_{13} = 8.375;$ $b_{23} = -10.625; b_{123} = 6.125$	Product-28 = 49% Aluminium A-4 = 18% Product-14 = 22%
Density	$b_0 = 50.625; b_1 = 5.25;$ $b_2 = 6.15; b_3 = -0.75;$ $b_{12} = 0.37; b_{13} = 2.375;$ $b_{23} = -0.65; b_{123} = 0.5$	
The content of the binder components 10%		
Specific impulse	$b_0 = 100.65; b_1 = 18.12;$ $b_2 = 10.15; b_3 = -0.15;$ $b_{12} = 9.375; b_{13} = 11.35;$ $b_{23} = -8.25; b_{123} = 7.5$	Product-28 = 50% Aluminium A-4 = 18% Product-14 = 22%
Density	$b_0 = 60.625; b_1 = 8.25;$ $b_2 = 7.15; b_3 = -0.25;$ $b_{12} = 0.75; b_{13} = 3.75;$ $b_{23} = -0.25; b_{123} = 0.95$	
The content of the binder components 9%		
Specific impulse	$b_0 = 115.65; b_1 = 22.12;$ $b_2 = 14.15; b_3 = -0.1;$ $b_{12} = 11.75; b_{13} = 14.5;$ $b_{23} = -6.5; b_{123} = 9.75$	Product-28 = 45% Aluminium A-4 = 16% Product-14 = 30%
Density	$b_0 = 70.625; b_1 = 9.5;$ $b_2 = 8.65; b_3 = -0.2;$ $b_{12} = 0.925; b_{13} = 4.65;$ $b_{23} = -0.2; b_{123} = 1.75$	
The content of the binder components 8%		
Specific impulse	$b_0 = 125.85; b_1 = 25.70;$ $b_2 = 16.45; b_3 = -0.04;$ $b_{12} = 15.25; b_{13} = 17.125;$ $b_{23} = -3.25; b_{123} = 11.675$	Product-28 = 44 % Aluminium A-4 = 19 % Product-14 = 29 %
Density	$b_0 = 80.25; b_1 = 10.275;$ $b_2 = 9.125; b_3 = -0.125;$ $b_{12} = 1.625; b_{13} = 5.785;$ $b_{23} = -0.135; b_{123} = 2.95$	

Table 10 – The results of the optimization of the experimental plans in the study of the energy characteristics of the prescription composition

Criterion optimization	Cost of sales experiment, conv. units	Cost of sales optimal plan, conv. units	Win	Program account time, s
The content of the binder components 11%				
Specific impulse	515	198	2.60	0.02
Density	475	196	2.42	0.01
The content of the binder components 10%				
Specific impulse	548	210	2.41	0.01
Density	500	200	2.53	0.01
The content of the binder components 9%				
Specific impulse	570	218	2.62	0.01
Density	526	198	2.67	0.01
The content of the binder components 8%				
Specific impulse	610	226	2.72	0.02
Density	552	208	2.65	0.02

CONCLUSIONS

In this work, the urgent task of developing a prescription composition with a thermodynamic assessment of the parameters and manufacturing technology of MSRF, obtaining a sequence of experiments during the experiment, optimized by the method of “jumping frogs”, ensuring the minimum cost of its implementation, is solved.

A method and software have been developed that implement the optimization of multifactorial design of experiments using the “jumping frogs” algorithm. The experiment plans that are optimal in terms of implementation cost are obtained, and also the winnings in the optimization results are shown compared to the initial cost of the experiment. The workability and effectiveness of the proposed method are proved by the examples of the study of the recipe composition with the thermodynamic estimation of parameters according to the energy characteristics of solid mixed rocket fuel. The study showed that the search for an optimal or close to the optimal design of the experiment using the method of “jumping frogs” gave good results. The gains obtained as a result of optimization using this method are significant. The application of the developed method and software based on the use of the “jumping frogs” algorithm is effective for a number of factors $k \geq 3$, since this method significantly reduces the number of permutations of the experiment planning matrix.

Taking into account the results of the study (table 10), when optimizing the cost of specific impulse and fuel density using the obtained coefficients of mathematical models, we can draw the following conclusions on the optimal ratios of the components of the MSRF:

- for the content of the binder components 11%: the content of the components should correspond to: product-28 – 49%, A-4 – 18%, product-14 – 22%;
- for the content of the binder components 10%: the content of the components should correspond to: product-28 – 50%, A-4 – 18%, product-14 – 22%;
- for the content of the binder components 9%: the content of the components should correspond to: product-28 – 45%, A-4 – 16%, product-14 – 30%;
- for the content of the binder components 8%: the content of the components should correspond to: product-28 – 44%, A-4 – 19%, product-14 – 29%.

It should be noted that with an increase in the average pressure in the combustion chamber of the engine, it is advisable to increase the degree of expansion of the nozzle in order to achieve a higher specific impulse, however, this will lead to a significant increase in the design of the nozzle block, which will reduce the weight ratio of the product.

With a decrease in the binder content of more than 1%, the increase in specific impulse is less than 1%, which is insignificant. However, a decrease in the binder content in the SRF formulation to a level of less than 10%

may lead to critical changes in the operational characteristics at the stages of SRF manufacturing, product operation, etc.

The scientific novelty of the work is that for the first time a method is proposed for constructing optimal plans for multifactor experiments based on the use of the “jumping frogs” algorithm, which will make it possible to construct optimal experimental plans without completely enumerating the experimental permutation options.

The practical significance of the results of the work lies in the fact that software has been developed that implements the proposed method, as well as experiments have been carried out that have confirmed its efficiency and allow scientists to recommend it in practice when constructing optimal planning matrices for experiments.

Prospects for further research are the application of the developed software on a wider range of practical tasks.

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ЗАСТОСУВАННЯ МЕТОДУ «СТРИБАЮЧИХ ЖАБ» ДЛЯ ДОСЛІДЖЕННЯ ТА ОПТИМІЗАЦІЇ ТЕХНОЛОГІЧНОГО ПРОЦЕСУ

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АНОТАЦІЯ

Актуальність. Запропоновано застосування методу «стрибаючих жаб» для побудови оптимальних планів експериментів за вартісними (часовими) витратами при дослідженні технологічних процесів та систем, що дозволяють здійснювати над ними активний експеримент.

Об'єкт. Методи оптимізації за вартісними (часовими) витратами, основані на застосуванні алгоритму пошуку «стрибаючих жаб».

Метою роботи є отримання результатів оптимізації шляхом оптимізації за допомогою алгоритму «стрибаючих жаб» за вартісними (часовими) витратами планів повного факторного експерименту.

Метод. Запропоновано метод побудови за вартісними (часовими) витратами реалізації матриці планування експерименту з використанням алгоритму «стрибаючих жаб». На початку вводиться кількість факторів і вартість переходів для кожного рівня факторів. Потім з урахуванням введених даних формується початкова матриця планування експерименту. Метод «стрибаючих жаб» визначає найбільш «успішну жабу» та найменшу вартість переходів між рівнями для кожного з факторів. Після цього виконуються перестановки «жаб». «Жаба» прагне до найбільш «успішних» і, за умови, що вона залишається поруч, залишається на місці. Також розраховується вигреш порівняно з початковою вартістю (часом) експерименту.

Результати. Розроблено програмне забезпечення, що реалізує запропонований метод, який використовувався для проведення обчислювальних експериментів для вивчення властивостей цих методів при вивченні технологічних процесів і систем, що дозволяють здійснювати над ними активний експеримент. Отримані результати оптимальних планів експериментів за вартісними (часовими) витратами порівнюються з початковою вартістю експерименту та розраховується вигреш у порівнянні з початковим планом експерименту.

Висновки. Проведені експерименти підтвердили працездатність запропонованого методу та програмного забезпечення, яке його реалізує, а також дозволяє рекомендувати його для практичного використання при побудові оптимальних матриць планування експериментів.

КЛЮЧОВІ СЛОВА: оптимальний план, алгоритм «стрибаючих жаб», оптимізація, планування експерименту, вартість, вигреш.

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ПРИМЕНЕНИЕ МЕТОДА «ПРЫГАЮЩИХ ЛЯГУШЕК» ДЛЯ ИССЛЕДОВАНИЯ И ОПТИМИЗАЦИИ ТЕХНОЛОГИЧЕСКОГО ПРОЦЕССА

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АННОТАЦИЯ

Актуальность. Предложено применение метода «прыгающих лягушек» для построения оптимальных планов экспериментов по стоимостным (временным) затратами при исследовании технологических процессов и систем, позволяющих осуществлять над ними активный эксперимент.

Объект. Методы оптимизации по стоимостным (временным) затратам, основанные на применении алгоритма поиска «прыгающих лягушек».

Целью работы является получение результатов оптимизации путем оптимизации с помощью алгоритма поиска «прыгающих лягушек» по стоимостным (временным) затратами планов полного факторного эксперимента.

Метод. Предложен метод построения по стоимостным (временным) затратами реализации матрицы планирования эксперимента с использованием алгоритма «прыгающих лягушек». В начале вводится количество факторов и стоимость переходов для каждого уровня факторов. Затем с учетом введенных данных формируется начальная матрица планирования эксперимента. Метод «прыгающих лягушек» определяет «успешную лягушку» по наименьшей стоимости переходов между уровнями по каждому из факторов. После этого выполняются перестановки «лягушек». «Лягушка» стремится к наиболее «успешной» и, при условии, что находится рядом, остается на месте. Также рассчитывается выигрыш по сравнению с начальной стоимостью (времени) эксперимента.

Результаты. Разработано программное обеспечение, реализующее предложенный метод, который использовался для проведения вычислительных экспериментов для изучения свойств этих методов при изучении технологических процессов и систем, позволяющих осуществлять над ними активный эксперимент. Полученные результаты оптимальных планов экспериментов по стоимостным (временным) затратами сравниваются с начальной стоимостью эксперимента и рассчитывается выигрыш по сравнению с первоначальным планом эксперимента.

Выводы. Проведенные эксперименты подтвердили работоспособность предложенного метода и программного обеспечения, которое его реализует, а также позволяет рекомендовать его для практического использования при построении оптимальных матриц планирования экспериментов.

КЛЮЧЕВЫЕ СЛОВА: оптимальный план, алгоритм «прыгающих лягушек», оптимизация, планирование эксперимента, стоимость, выигрыш.

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