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Improving Energy Efficiency of Grain Cleaning Technology

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Abstract: The relevance of the research topic was substantiated, and the purpose and objectives of the study were formulated. It was determined that the energy efficiency of the grain cleaning process can be evaluated only when all the machines operate in a single production line and are coordinated in productivity. Research on energy savings and energy efficiency in the technological process of post-harvest grain treatment using grain cleaning units by implementing the method of mathematical experiment planning (MEP) was conducted. The method is based on transforming the initial mathematical models of various research objects into a model in the form of regression equations convenient for solving the problems of research, analysis and optimization of the object. For the first time, the mathematical description of the target function was performed by conducting a multifactorial experiment based on second-order design. The research produced adequate second-order regression equations, making it possible to determine the minimum specific consumption of electricity for the technological process of post-harvest grain treatment at grain cleaning facilities, while complying with the agrotechnical requirements for the quality of the cleaned grain. The problem of optimization of the research object was solved by mathematical transformations, which enabled obtaining graphical and analytical interpretations of the optimum area. For this purpose, the canonical transformation of the mathematical model and the method of two-dimensional cross-sections of the response surface were used. Research has led to the development of scientifically based standards of specific electricity consumption for grain cleaning processing schemes, which serve as criteria for evaluating energy savings in the technological processes.

Keywords: mathematical experiment; energy saving; experiment planning; grain cleaning unit; energy efficiency; post-harvest grain treatment

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1. Introduction

Energy shortages in the global market pose a necessity to preserve electric energy, which in turn requires a consistent analysis of the efficiency of electricity consumption [1–3]. The regulatory and technical basis for energy savings, according to the Law of Ukraine "On Energy Saving" is formed by standards that lay the foundation for the application of economic measures of energy-saving management. Presently, over 11 standards are in force in the field of energy saving. Another set of standards is under development. Sustainable energy consumption during the post-harvest treatment of grain using grain cleaning units of agricultural enterprises can be attained by providing the rated load on the drive electric motors of the production lines, which ensures grain cleaning with minimal power consumption and is a criterion in evaluating its use [4,5].

The aim of the study is to determine the operating modes to optimize the electrical equipment of a ZAV-40 grain cleaning unit. The task of the research is to determine the operating modes of post-harvest grain production lines providing minimum electricity consumption within the input parameter change range.

Among the technical means of complex mechanization of post-harvest grain treatment, ZAV-40 grain cleaning units are rather widespread. In response to the transition to new methods of economic management, prerequisites for transforming energy saving from an abstract factor of economy into a real necessity began to form. For the last 10–15 years, post-harvest technology on farms based on stationary grain cleaning units ZAV-10–ZAV-50, and KZS-10–KZS-50 account for up to 60–70% of grain and seeds processed on farms. In order to upgrade existing equipment, IMEA UAAS in cooperation with JSC "Vibroseparator" created domestic complexes for processing food and feed grains with a capacity of 25 and 50 t/h. However, regardless of the introduction of new units and complexes, for many years, the bulk of grain was cleaned on the equipment available on farms, so a number of additional measures need to be taken to ensure that the equipment is functional at a minimum specific electricity consumption.

To ensure the high-quality post-harvest treatment of grain, researchers [6] have suggested using a linear induction motor for driving vibration centrifugal separators, which directs the movement of the working body without any transducers. The authors of [7,8] obtained a mathematical model of a grain separator and conducted experimental studies confirming the adequacy of the model. The simulation error did not exceed 9%. The authors of [9,10] carried out research and suggested using a linear induction drive instead of the classical mechanic drive of the grain cleaning unit and the grain separator. To solve the problem, a mechatronic module "linear electric drive—drum sieve" was suggested, which led to a significant increase in power. In their research, the authors of [11] proved that the pulse operating mode of the MVR-2 (SU-0.1) machine increases the performance by 20% when using a linear electric drive. Thus, mathematical modelling has been widely used in research of the technological processes of post-harvest grain treatment.

Different authors consider ways to improve the designs of working machines of grain cleaning production lines. Energy- and resource-saving grain cleaning machines for separation of the light impurities of seeds [12] have been developed. The quality of grain cleaning depends on the number of fan revolutions. According to theoretical and experimental studies, the separation of about 85% of light impurities of grain has been achieved. A grain cleaning machine for fractional technology of fodder grain crushing [13] has been developed and theoretically investigated. Research on the pneumatic system has been carried out by mathematical modelling, which allows theoretical testing of its operability. For small farms, a grain cleaning machine [14] was developed and tested, which had low specific metal consumption and lower energy consumption. The intervals of parameters and operating modes of the grain cleaning machine were selected.

Vibration machines are considered to be the basis of future technologies [15]. The authors obtained a mathematical model of a cleaning machine with a vertical rotation axis, developed a calculation method, and calculated the structural parameters of an automatic vibrator. The designs and operating parameters of the screening module of the grain cleaning machine [16] have been studied with a view to investigating the improvement of the sieves' cleaning efficiency by substantiating kinematic operating modes.

Recently, much attention has been paid to the technological process of the diameter fan in a rotating coordinate system [17–19]. The authors substantiated the parameters of its operation based on the mathematical model of the fan's technological process. The authors of [20–22] suggest a separator with small power capacity of pneumatic separation. Improved disc separators are suggested by [23] for better grain cleaning. It is recommended to use the specific electricity consumption method [24,25] in calculating the power of the electric motor.

As can be seen from previous research that mathematical modelling also identifies directions for further improvement of machines for cleaning grain with air flow [26]. Mathematical modelling of grain separation in a grain cleaning machine [27,28] and the study of its sieve frame operation [29] confirm the adequacy of mathematical modelling. The evaluation of mathematical models in separating light impurities in sediment chambers of grain cleaning machines has been carried out in parallel with experimental studies [30]. The generalized mathematical model of operating of screening machines is presented in [31].

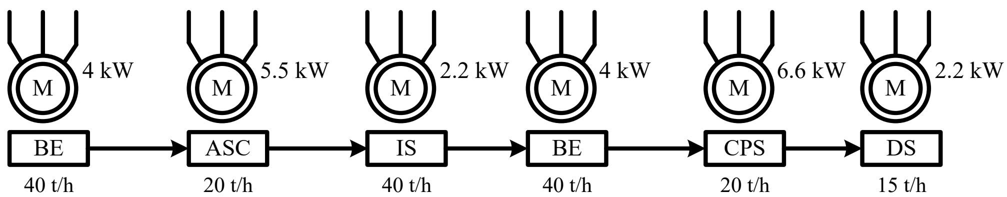
Studies of several multifactorial experiment designs with a minimum number of transition levels of factors [32,33] have been conducted. The authors recommend the wide use of active experiments in the research of technological processes, devices, and systems, where possible. Environmental issues such as dust emission into the environment during grain cleaning [34,35] and the emission of gases and heat during grain drying [36] are also relevant issues of our time. The developed methodology for determining the parameters of the air-sieve scalper separator air flow [37] makes it possible to make adjustments while determining rational and optimal parameters and operating modes of the pneumatic system. This increases the efficiency of the air-sieve separator and reduces its energy consumption.

The analysis of literary sources shows that the evaluation of the energy efficiency of the technological process of grain cleaning is only possible when all the machines, the improvement of which is suggested by the authors, work in a single production line and are coordinated in performance.

2. Technological Process of ZAV-40 Grain Cleaning Unit

The unit is designed for cereal zone farms of a country with annual grain production volume of 10–12 thousand tons at a harvest humidity of up to 16%. Unlike ZAV-10 and ZAV-20, the set of machines and equipment of a ZAV-40 facility (Figure 1) includes: two bucket elevators (BE), two air screen cleaners (ASC), an intermediate screw (IS), two centrifugal pneumatic separators (CPS), and two disc separators (DS). The arrangement of the equipment allows working on four technological schemes.

First scheme, cleaning on one of the lines: air screen cleaning, centrifugal pneumatic separator, disc separator cleaning (Figure 1a). Second scheme: same as the first scheme, but without disc separator cleaning (Figure 1b). Third scheme: same as the first scheme, but with simultaneous operation of the first and second lines (Figure 1c). Fourth scheme: same as the second scheme, but with parallel operation of the first and second lines (Figure 1d).



(**a**)

Figure 1. *Cont.*

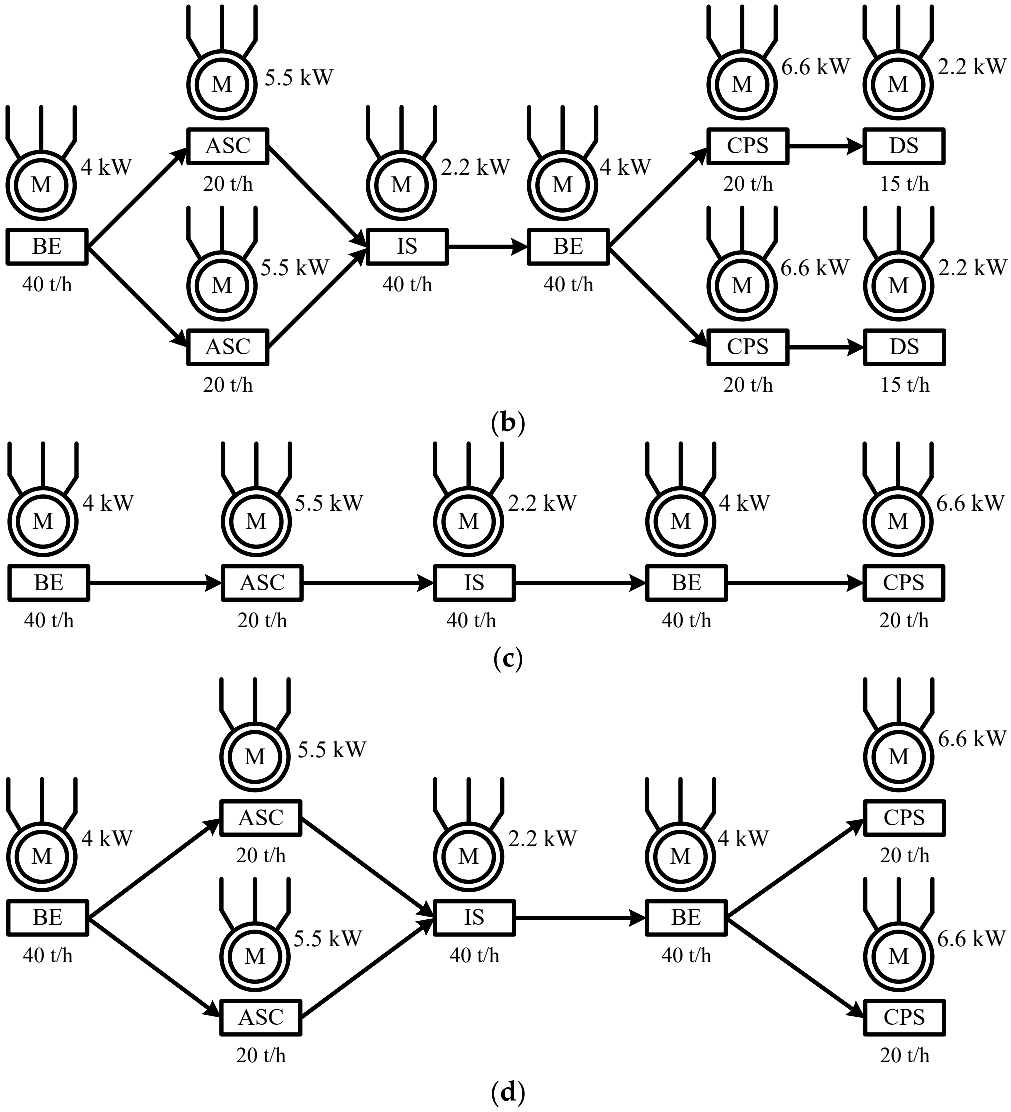


Figure 1. Technological schemes of ZAV-40 grain cleaning unit: M—induction motor, BE—bucket elevator, ASC—air screen cleaner, IS—intermediate screw, CPS—centrifugal pneumatic separator, DS—disc separator.

3. Materials and Methods

To study the influence of various factors on the energy intensity of the grain cleaning process on the ZAV-40 unit, the method of mathematical experiment planning (MPE) was used, which was first substantiated and applied by Novakovskaia and Adamenko [4] and is aimed at design optimization of stepper and induction micromotors. This method is based on transforming the initial mathematical models of various research objects into a model in the form of regression equations, convenient for analysis and optimization of the object. The name of the method is explained by the fact that the methodology of restructuring the initial mathematical model of the research object is entirely based on the use of a mathematical apparatus and the methodology of the classical theory of experiment planning.

Since the dependence of specific electricity consumption on performance is non-linear [4], second-order plans were used to obtain the regression equation. The selection of factors, variability intervals, and levels was based on the analysis of a priori information. The following variables were selected: x_1—unit capacity, Q, t/h; x_2—connected capacity of the electric motors of the unit's production line, P, kW; x_3—load factor of the electric motors of the production line, K_l (Table 1).

Table 1. Factor levels and variability intervals for ZAV-40.

Factor Variability Levels	Factors in Nominal Units	Factors in Physical Units		
		Q, t/h x_1	P, kW x_2	K_1, r.u. x_3
Upper $X_{i,u}$	$x_{i,u}$ = +1	40.0	45.0	0.8
Lower $X_{i,l}$	$X_{x,l}$ = −1	20.0	25.0	0.5
Base $X_{i,0}$	$x_{i,0}$ = 0	30.0	35.0	0.65
Variability intervals ΔX_i	Δx_i = ±1	10.0	10.0	0.15
Star arm size				
+α	+1.215	42.85	47.15	0.832
−α	−1.215	17.85	22.85	0.468

Second-order polynomials [4] were used to adequately describe the optimum domain:

$$y = b_0 + \sum_{i=1}^{n} b_i \cdot x_i + \sum_{i<j}^{n} b_{i,j} \cdot x_i \cdot x_j + \sum_{i=1}^{n} b_{ii} x_i^2 + \ldots$$

where y—target function; b_0, b_i, b_{ij}, b_{ii}—coefficients of the regression equation; x_i, x_j, x_i^2—nominal values of factors.

Such a mathematical model can be obtained on the basis of second-order designs, for example, the orthogonal central compositional design (OCCD) or the rotatable central compositional design (RCCD), as well as D-optimal designs. In [4], second-order OCC designs are recommended for optimization. OCCD means planning of the experiment on five levels, which can be presented in nominal units in the following form:

$$(1)\ -\alpha;\ (2)\ -1;\ (3)\ 0;\ (4)\ +1;\ (5)\ +\alpha,$$

where α—arm size of the star points.

The statistical processing of data was performed. For the second-order orthogonal central compositional design (OCCD), the orthogonality of all column vectors of the design matrix is the optimization criterion, including column vectors for all quadratic terms x_i^2 (i = 1, 2 . . .) and zero term x_0.

4. Results and Discussion

The mathematical model [1] $\widetilde{y} = f(x_1, x_2, x_3)$ for ZAV-40 in the form of a second-order regression equation is as follows:

$$\widetilde{y} = 1.012 - 0.313x_1 + 0.283x_2 + 0.228x_3 - 0.102x_1x_2 - 0.082x_1x_3 + 0.07x_2x_3 - 0.102x_1^2 + 0.084x_2^2 + 0.084x_3^2 \quad (1)$$

The analysis of Equation (1) shows that the function of specific electricity consumption has an extremum. In the physically acceptable range of operating modes of the production line, the function of specific electricity consumption is continuous and has no other extreme points, which means that at the estimated points of minimum, the function reaches the lowest value [4].

The tasks of static optimization of objects are solved by search methods. In addition, some mathematical transformations allow a graphical and analytical interpretation of the optimum domain. For this purpose, canonical transformation of the mathematical model and the method of two-dimensional cross-sections of the response surface were used. According to Equation (1), the specific electricity consumption for the ZAV-40 unit is calculated depending on the performance, capacity, and load factor of the electrical equipment, which results in obtaining corresponding theoretical response surfaces. To analyse Equation (1) by method of two-dimensional cross-sections, the obtained second-order regression equation was differentiated for each factor and set to zero:

$$
\begin{aligned}
\frac{\partial \tilde{y}}{\partial x_1} &= -0.313 - 0.102x_2 - 0.082x_3 - 0.204x_1 = 0; \\
\frac{\partial \tilde{y}}{\partial x_2} &= 0.283 - 0.102x_1 + 0.07x_3 + 0.168x_2 = 0; \\
\frac{\partial \tilde{y}}{\partial x_3} &= 0.228 - 0.082x_1 + 0.07x_2 + 0.168x_3 = 0.
\end{aligned} \quad (2)
$$

After solving the system of equations, coordinates of the centre were obtained in coded units:

$$x_{1S} = -0.396;\ x_{2S} = -1.548;\ x_{3S} = -0.906;\ y_S = 0.894,$$

which correspond to the following values of the factors and the target function in physical units:

$$Q = 40\ \text{t/h};\ P = 25\ \text{kW};\ K_l = 0.583.$$

The optimum value of the target function is equal to $W_{sp.}$ = 0.894 kW·h/t.

The possible two-dimensional sections with the most practical significance for the specific electricity consumption were considered.

1. Two-dimensional cross-section of the response surface characterizing the connected capacity and the load coefficient of electric motors (Figure 2) at x_1 = 0:

$$
\begin{aligned}
&\frac{\partial \tilde{y}}{\partial x_2} = 0.283 + 0.07x_3 + 0.168x_2 = 0; \\
&\frac{\partial \tilde{y}}{\partial x_3} = 0.228 + 0.07x_2 + 0.168x_3 = 0; \\
&x_{2S} = -1.35;\ \ x_{3S} = -0.79;\ \ y_S = 0.73,
\end{aligned} \quad (3)
$$

the values of factors in physical units is as follows:

$$P = 21.5\ \text{kW};\ K_l = 0.5\ \text{and}\ W_{sp.} = 0.73\ \text{kW·h/t}.$$

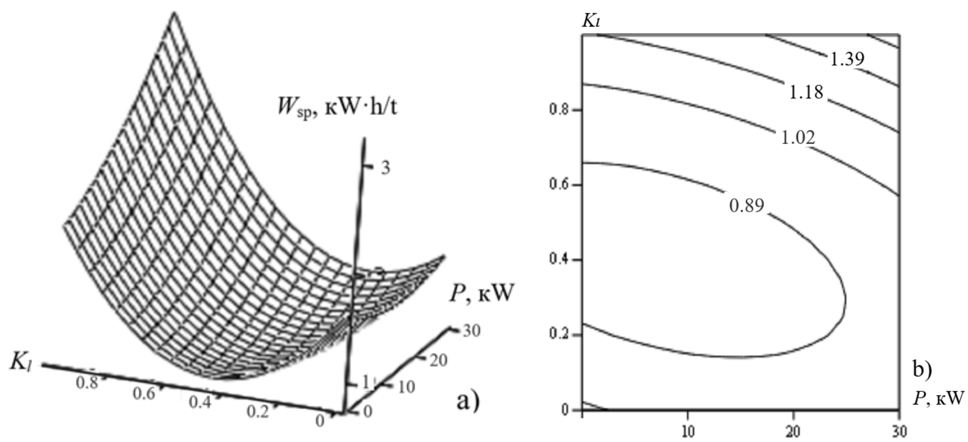


Figure 2. Response surface of the target function (**a**) and its two-dimensional cross-sections (**b**) for ZAV-40 at x_1 = 0.

For canonical transformation of the equation, the following system was solved:

$$f(\text{B}) = \begin{vmatrix} 0.168 - \text{B} & 0.5 \cdot 0.07 \\ 0.5 \cdot 0.07 & 0.168 - \text{B} \end{vmatrix} = (0.168 - \text{B}) \cdot (0.168 - \text{B}) - 0.0012 = 0.$$

The eigenvalues of this characteristic equation are

$$\text{B}_{22} = 0.13,\ \text{B}_{33} = 0.206.$$

The canonical equation takes the following form:

$$Y - 0.73 = 0.13X_2^2 + 0.206X_3^2.$$

2. Two-dimensional cross-section of the response surface characterizing the unit capacity and the load coefficient of electric motors (Figure 3) at x_2 = 0:

$$\begin{aligned} \frac{\partial \tilde{y}}{\partial x_1} &= -0.313 - 0.082x_3 - 0.204x_1 = 0; \\ \frac{\partial \tilde{y}}{\partial x_3} &= 0.228 - 0.082x_1 + 0.168x_3 = 0; \\ x_{1S} &= -0.83;\ x_{3S} = -1.76;\ y_S = 0.94, \end{aligned} \tag{4}$$

the values of factors in physical units are equal to

$$Q = 31.7\ \text{t/h};\ K_l = 0.39 \text{ and } W_{sp.} = 0.94\ \text{kW·h/t}.$$

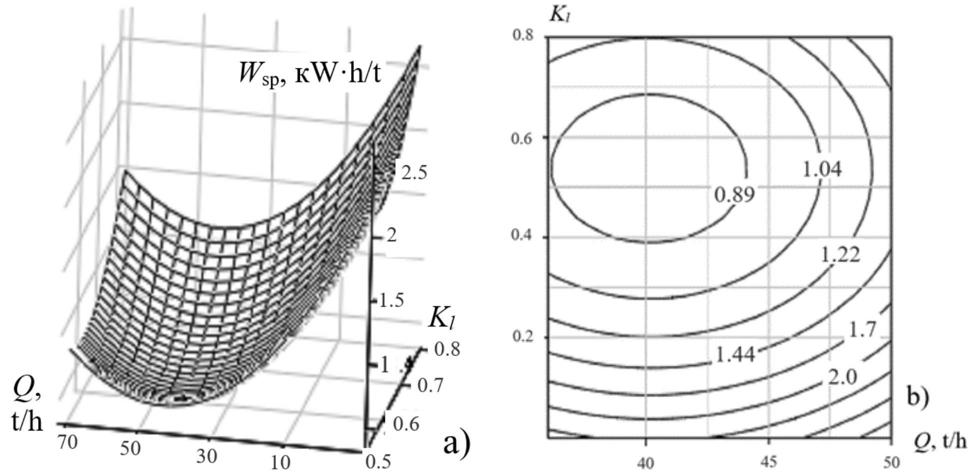


Figure 3. Response surface of the target function (**a**) and its two-dimensional cross-sections (**b**) for ZAV-40 at x_2 = 0.

For canonical transformation of the equation, the following system was solved:

$$f(\text{B}) = \begin{vmatrix} -0.204 - \text{B} & -0.5 \cdot 0.082 \\ -0.5 \cdot 0.082 & 0.168 - \text{B} \end{vmatrix} = (-0.204 - \text{B}) \cdot (0.168 - \text{B}) - 0.0017 = 0$$

The eigenvalues of this characteristic equation are

$$\text{B}_{11} = -\ 0.208,\ \text{B}_{33} = 0.172.$$

The canonical equation takes the following form:

$$Y - 0.941 = -0.208X_1^2 + 0.172X_3^2.$$

3. Two-dimensional cross-section of the response surface characterizing the unit capacity and the connected capacity of electric motors (Figure 4) at x_3 = 0:

$$\begin{aligned} \frac{\partial \tilde{y}}{\partial x_1} &= -0.313 - 0.102x_2 - 0.204x_1 = 0; \\ \frac{\partial \tilde{y}}{\partial x_2} &= 0.283 - 0.102x_1 + 0.168x_2 = 0; \\ x_{1S} &= -0.53;\ \ x_{2S} = -2.01;\ \ y_S = 0.81, \end{aligned} \tag{5}$$

the factors in physical units are equal to

$$Q = 24.7\ \text{t/h};\ P = 4.9\ \text{kW and } W_{sp.} = 0.81\ \text{kW·h/t}.$$

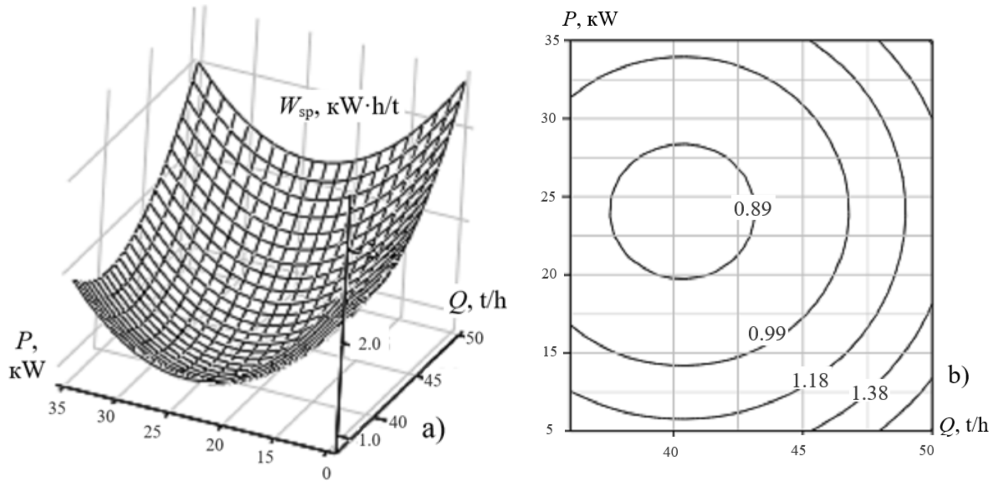


Figure 4. Response surface of the target function (**a**) and its two-dimensional cross-sections (**b**) for ZAV-40 at $x_3 = 0$.

For canonical transformation of the equation, the following system was solved:

$$f(\text{B}) = \begin{vmatrix} -0.204 - \text{B} & -0.5 \cdot 0.102 \\ -0.5 \cdot 0.102 & 0.168 - \text{B} \end{vmatrix} = (-0.204 - \text{B}) \cdot (0.168 - \text{B}) - 0.0026 = 0.$$

The eigenvalues of this characteristic equation are

$$\text{B}_{11} = -\ 0.21,\ \text{B}_{22} = 0.174.$$

The canonical equation takes the following form:

$$Y - 0.81 = -0.21X_1^2 + 0.174X_2^2.$$

With production development, the electrical load increases significantly, so the issues of electricity rationing are relevant [38]. Improving energy efficiency in the sector is a prerequisite for the transition to sustainable development [39,40]. The logic of calculating energy saving by increasing energy efficiency was investigated. To evaluate the energy efficiency of the power supply system in the sector, it is suggested to carry out electric drive simulation [41]. To promote energy saving in grain cleaning industry, it is suggested to use voltage stabilisers with energy saving function in the grids [42]. These devices save at least 10% of electricity and reduce losses in networks by up to 40%.

The conducted study [43] enabled making a comparative assessment of the estimated specific electricity consumption for various technological schemes according to the proposed Model (1), which led to the development of scientifically based electricity consumption standards (Table 2).

In comparison with the previously existing standards of specific electricity consumption for grain cleaning [44], the standards developed by the authors (Table 2) are reduced by 18–22%. The recommended scientifically based standards of electric consumption are intended for departments of economics and planning of regional agricultural administrations to plan and manage electricity consumption for technological processes of grain cleaning on the production lines of grain storage facilities. Similar experimental [45] and theoretical [46] studies have been carried out for the first time by the authors for ZAV-20 and ZAV-25 [47] grain cleaning units, and scientifically based electricity consumption standards have been developed, as confirmed by the certificates of research results implementation. Corresponding studies are also being carried out for other grain cleaning units produced by industry.

Table 2. Recommended scientifically based norms of electricity consumption when cleaning grain on the production lines of the ZAV-40 grain cleaning unit.

Technological Schemes	Capacity, t/h	Calculated $W_{sp.}$, kW·h/t	Recommended Norms, kW·h/t
One production line with disc separators	15.0	1.274	1.347
One production line without disc separators	20.0	0.805	0.902
Two production lines with disc separators	30.0	1.271	1.342
Two production lines without disc separators	40.0	0.805	0.901

5. Conclusions

1. The conducted experimental and theoretical studies of the technological processes of post-harvest grain treatment on grain cleaning units showed that the energy consumption of the grain cleaning process is the most informative indicator for determining energy saving operating modes of electromechanical systems of grain storage facilities.
2. By analysing a priori information, the following were selected as the most significant factors influencing the power capacity of the grain cleaning process: the processing equipment productivity, the connected capacity, and the load factor of the electric power equipment.
3. For the first time, the methodology for the optimization of specific electricity consumption on the ZAV-40 grain cleaning unit on production lines using the MEP was developed, the essence of which lies in the application of the MEP theory to the mathematical model of the specified object of study.
4. Two-dimensional cross-sections of the response surface of the target function, which were obtained after processing the mathematical model of the ZAV-40 unit, allowed for determination of the optimal factors and rational levels of their variation. It was determined that the minimum specific electricity consumption for the unit in general occurs if the values of the factors most affecting the specific electricity consumption are as follows: Q = 40 t/h; p = 25 kW; K_l = 0.583; $W_{sp.}$ = 0.894 kW·h/t.
5. The recommended scientifically based electricity consumption standards for various technological schemes of wheat grain cleaning on ZAV-40 production lines are as follows:
   - one production line with disc separators: $W_{sp.}$ = 1.347 kW·h/t;
   - one production line without disc separators: $W_{sp.}$ = 0.902 kW·h/t;
   - two production lines with disc separators: $W_{sp.}$ = 1.342 kW·h/t;
   - two production lines without disc separators: $W_{sp.}$ = 0.901 kW·h/t.
6. The suggested optimization method for specific electricity consumption can be used while developing scientifically based standards of electricity consumption for new grain-cleaning units produced by industry.

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Nomenclature

ZAV-10–ZAV-50	Grain cleaning unit (Zernoochistitelnyiy Agregat Voronezhselmash) with production capacity of 10 to 50 t/h
KZS-10–KZS-50	Grain cleaning and drying complex (Kompleks Zernoochistitelno-Sushilnyiy) with a capacity of 10 to 50 t/h
MEP	Mathematical Experiment Planning
OCCD	Orthogonal Central Compositional Design
RCCD	Rotatable Central Compositional Design
Q	Capacity, t/h
P	Power, kW
$W_{sp.}$	Specific electricity consumption, kW·h/t
K_l	Load factor of the electric motors

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