Optimization of machine-tractor parameters units for target functions with minimum costs total energy

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Abstract. The article is aimed at developing the parameters and operating modes of a multifunctional unit for the simultaneous sowing of row crops and the introduction of the main and pre-sowing solid mineral fertilizers. The minimization of the target function in terms of the total energy consumption for the process is ensured by the combination of these technological operations in combination with the substantiation of the parameters and operating modes of the proposed unit, which ensures the introduction of a new resource-saving technology for sowing row crops. The difference between the methodological approach to solving the problem lies in the use of typical traction characteristics of tractors, linking their tractive power, tractive effort, working speed, specific fuel consumption of the engine in combination with the working width of the seeding unit, its traction resistance and operating conditions: type of soil, working length of rut, capacity of the fertilizer hopper, rate of consumption of seeds and fertilizers, etc. The standard indicators used in calculating the target function are taken from the reference literature. The urgency of the problem of reducing the energy intensity of the process is determined by a further increase in the competitiveness of the field crop production, where scientifically grounded parameters of machines and their mode of operation are of decisive importance. The regularities of the process and the dependence of the optimization criterion on the parameters and operating modes of the proposed multifunctional unit, obtained as a result of the research, make it possible not only to obtain their optimal value, but also to outline further directions for improving the design.

1. Introduction
A further increase in the competitiveness of field cultivation is inextricably linked with the parameters of machines for the mechanization of production machines for the mechanization of production processes and their efficiency.

Among the efficiency parameters, an important place is occupied by the energy intensity of production processes, which depends on the mass of machines used, their productivity, annual load, rational aggregation, fuel economy and efficient operation of equipment [1,2,3]. In this regard, the development of methods for determining the energy intensity of production processes is an urgent task.

According to literary sources [4], the production of field crop products in Russia is still labor-intensive and energy-intensive. So, for the production of 1 ton of grain, labor costs in Russia are 9 people/h, and in the USA - only 2.6; sugar beet, respectively, 4.5 and 1.1 people/h. The energy intensity of production in Russia is also 4-5 times higher than in the United States. For the production of 1 ton of
grain in Russia, 178 kg of standard fuel is consumed, while in the USA - only 45. The total energy consumption per 1 ha of farmland is 280 and 121 kg of standard fuel, respectively.

Reducing energy costs is determined by the applied technique and technology of cultivation of agricultural crops. Already when designing the structure of a new machine, the energy consumption of the process and other technical and economic indicators must be taken into account. We have performed calculations of the energy consumption of a multifunctional sowing unit according to the methodology of the Ministry of Agriculture and the All-Union Academy of Agricultural Sciences

2. Materials and methods
We have developed a mathematical model and an algorithm for optimizing the parameters of a multifunctional seeding unit. As the target function of the model, the total energy consumption for the production process of sowing, for example, corn, with the simultaneous introduction of pre-sowing and basic fertilizers is taken.

The proposed unit, as an object of inheritance, includes a corn seeder, on which tanks for the main fertilizer are mounted, fuel pipelines and feeding knives for incorporating fertilizers to a depth of 23-25 cm.

At such a depth, only potash and phosphorus fertilizers are embedded, nitrogen fertilizers are applied to the surface of the field and distributed during plowing over the entire layer. This design and technological feature of the unit provides both a decrease in the energy intensity of the process and an increase in the yield of the sown crop due to the rational distribution of fertilizers in the arable layer.

The mathematical model for optimizing the parameters and operating modes of the unit includes: variables (tractive effort of the tractor \( P_t \) in each gear, tractive power \( N_t \), travel speed \( \nu_p \), working width \( B_p \), specific fuel consumption \( G_t \), run length \( L_p \), capacity of the hopper for seeds and fertilizers \( V_b \)) and their limitations, as well as the target function \( E \) - the total energy consumption for the process of sowing maize with the introduction of the main fertilizer and with the sowing fertilizer. This criterion takes into account both direct and indirect energy costs. With regard to crop production, the energy assessment of machines and technology according to the methodology [5] includes direct energy consumption (mainly oil products) for the production of a unit of production or per 1 hectare of cultivated area, as well as indirect energy consumption (for the production of mechanization means, fertilizers, pesticides, etc.). In this case, the energy equivalents of a unit mass of machines and materials in J/kg are used [5].

The block diagram of the algorithm for optimizing the parameters of our unit is shown in Figure 1. It includes 16 operators, of which two cycles and one logical. The first five operators are needed to enter the initial data for the calculation, and the last one (16) - to print the results of solving the problem by the objective function. In the first five operators, the values of tractive effort \( P_t \) of the selected K-700 tractor of traction class 5 are entered for the aggregation of our multifunctional unit.

From the typical traction characteristic of the K-700 tractor [6], we select five \( P_t \) values and the corresponding values of the speed \( \nu_p \) at different gears, tractive power \( N_t \) and specific fuel consumption \( G_t \).

Further, this data is transmitted to the blocks of cycle 6 and 7, which, using the information received from operators 1-5, perform calculations: the working width of the unit \( B_p \) (operator 9), the number of cycles \( n_c \) during the operation of the unit (operator 11), the utilization factor of the working time of the shift \( \tau \) (operator 12) and the productivity of the unit \( W \) for 1 hour of shift time (operator 13).

Next, control is transferred to the operator 14 which calculates the objective function \( E \), after a cyclical calculation, finding \( E_{\text{min}} \) prints out the values of the initial data \( (P_t, \nu_p, G_p, N_t) \) and the optimal parameters, \( \tau, W, E_{\text{min}} \tau \), for each block (1-5) of the unit while ensuring the operating conditions \( (L_p, V_b) \).
Figure 1. Block diagram of the optimization of the parameters and operating modes of the unit for sowing corn with fertilization.

After that, control is transferred to operator 2, which performs similar calculations and so on up to operator 5.

For example, Table 1 shows the calculations of one of the blocks on a computer.
Table 1. Results of calculations of the third block.

| Initial data of 3 blocks | Calculation results |
|-------------------------|---------------------|
| \( P_t = 32 \)          | \( B_p' = 4.99 \)   |
| \( \nu_p = 9.1 \)       | \( B_p = 4.9 \)     |
| \( G_t = 34.2 \)        | \( n_c' = 166.68 \) |
| \( N_t = 82.5 \)        | \( n_c = 167 \)     |
|                         | \( \tau = 0.986 \)  |
|                         | \( W = 4.496 \)     |

Thus, a decision is made to use the multifunctional unit offered by us for the K-700 tractor, its optimal parameters, operating mode and minimum energy consumption.

3. Results and its discussion

Having received the values of the optimal parameters and operating modes of the unit, we analyze the results of the solution. It is better to analyze the obtained dependences, for example, the optimization criterion \( E \) on the unit parameters: on the change in tractive effort (Figure 2), on the width of the unit capture \( B_p \) (Figure 3), on the speed \( \nu_p \) (Figure 4).

**Figure 2.** Dependence of the specific total energy consumption during the operation of the unit on the tractive effort of the tractor.

**Figure 3.** Dependence of the specific total energy consumption during the operation of the unit on the width of its capture.
Analyzing the dependence of energy consumption on the traction force of the tractor (Figure 2), we can conclude that its minimum value takes place for the force of 32 kN of the K-700 tractor. With an increase in tractive effort over the optimal one to 44 kN or its decrease to 20 kN leads to an increase in energy intensity, which reduces the efficiency of crop production. So, with a pulling force of 32 kN, the minimum value of the energy intensity of the sowing process with simultaneous fertilization is 629 MJ/ha. With a force of 36 kN - already 647, and with 44 kN - 731 or increases by 14% from the optimum. The reason for such an increase in energy consumption can be explained by analyzing the formula for the objective function $E$ (operator 14).

With an increase in tractive effort, the value of traction power $N_t$ increases, which, according to the formula, is multiplied by 1.14. In addition, the working width of the aggregate $B_r$ increases, which is multiplied by the empirical coefficient 162. And even an increase in the productivity of the aggregate due to an increase in its working width does not compensate for the increase in specific energy consumption.

The operating speed of the unit is optimized in the same way (Figure 4). So, at an optimal speed of 9.1 km/h, the minimum of the objective function is 629 MJ/ha. An increase and decrease in the working speed from the optimal value causes an increase in energy intensity, respectively, to 691 and 731 MJ/ha.

The same is true for the working width of the unit (Figure 3). The minimum value of the objective function (optimum) at a working width of 4.9 m increases by 14% at a width of 7 m and by 9% at a working width of an aggregate of 2.8 m.

The analyzed dependences were obtained when the unit was operating on a field with a run length of 1500 m and with a fertilizer hopper capacity of 4 m$^3$.

The approximation of the dependencies in figures 2…4 showed the following results:

Dependence of energy intensity $E$ on tractive effort $P_t$:

$$E = \sqrt{764,54 \cdot P_t^2 - 46,49 \cdot 10^3 \cdot P_t + 1,1 \cdot 10^6}$$  

(1)

Dependence of energy consumption on the working width of the unit:

$$E = \sqrt{24964 \cdot B_r^2 - 230710 \cdot B_r + 926720}$$  

(2)

Energy intensity versus operating speed:

$$E = 7,11 \cdot \frac{10^6}{v_p} + 79,45 \cdot 10^3 \cdot v_p - 1,11 \cdot 10^6$$  

(3)
The reliability of the dependences obtained is confirmed by the Cochran criterion [7]: the calculation for its value in all cases is less than the tabular value:

1. \( G_p = 0.4 \) and \( G_r = 0.77, \)
2. \( G_p = 0.44 \) and \( G_r = 0.768, \)
3. \( G_p = 0.45 \) and \( G_r = 0.77. \)

4. Conclusion

As a result of the studies carried out, the possibility of using typical traction characteristics of tractors on various soil backgrounds to optimize the parameters and operating modes of machines aggregated with them has been proved. A mathematical model and an algorithm for optimizing the parameters and operating modes of the unit have been developed using the objective function of the minimum unit consumption of total energy for the process of sowing corn with the simultaneous introduction of pre-sowing and basic fertilizers.

The minimum value of these costs was 629 MJ/ha when working with a tractor of traction class 5 at an operating speed of 9.1 km/h, with a working width of 4.9 m, a fertilizer hopper capacity of 4 m\(^3\) with a run length of 1500 m. The dependences of the process optimization criterion on the tractive effort of the tractor, the working width of the unit and the speed of movement are obtained, the reliability of which is confirmed by the Cochran criterion.

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