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Development of Effective Arable Units for Dump Plowing

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Abstract*: This article presents the results of the development of a mathematical model and a flowchart for optimizing the workflow of dump plowing with the simultaneous application of mineral fertilizers, as well as additional crumbling and leveling of the soil proposed by the authors of a machine-tractor unit. The optimal power of the tractor engine, its mass, the width of the implement and its mass, the operating speed and the optimization criterion value - the minimum total energy costs for the process of plowing with related works (fertilizing, leveling the soil) were obtained. The technical and operational indicators of modern dump plows are analyzed and the most effective ones are selected. New directions of increasing the efficiency of arable units on dump plowing are presented.

***Keywords* : arable unit, energy intensity, total energy costs, modeling, optimization, plowing, efficiency.**

I. INTRODUCTION

The production of competitive crop products requires increased efficiency, including plowing. Plowing remains a long-term perspective as the main method of tillage, despite its serious drawbacks on the harmful effects of the working bodies of dump plows on the destruction of the soil structure, the destruction of beneficial microorganisms, the loss of carbon, etc. Although plowing sprays soil less than disk implements, it is still required new ways to destroy the soil. Plowing is the most unproductive, expensive and most energy-intensive technological operation: it accounts for up to 20 and more kg of fuel per each hectare of arable land [1]. In this regard, further improvement of the design of dump plows, which should increase the quality of work, labor productivity, reduce fuel consumption and costs, is of particular relevance.

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In addition to these shortcomings, dump plowing in the cultivation technology has indisputable advantages compared to other methods of tillage, which are well known [1]. Arable aggregates with dump plows used in production affect the efficiency of the resulting products in different ways. The purpose of our article is to identify effective directions for improving the design and composition of arable units to eliminate the above disadvantages.

II. MATERIALS AND METHODS

One of the directions for increasing the efficiency of arable units is already successfully solved by domestic and revolving plows [2], which plow without furrows and ridges, level the soil qualitatively, contribute to increased labor productivity and fuel economy. The main method adopted in the work, a comparative analysis of various designs of plows and the synthesis of new technologies based on their application, modeling and optimization of parameters of arable units, which are the main task of our research. Arable units used in crop cultivation technologies must accurately take into account the agrotechnical requirements for each crop [3, 4, 5, 6]. For example, mineral fertilizers must be applied under the main tillage. These operations in existing technologies are performed separately, which increases costs. To increase the efficiency of plowing, fertilizer application, its incorporation into the soil by the plow bodies, cutting of the trimmed layer and leveling of the soil surface behind the plow is carried out in one pass of the unit across the field by our proposed unit [7, 8], shown in Figure 1.

The unit includes an energy device 1, a reversible plow with a supporting frame 2, rotated 180 ° relative to the horizontal axis, a rotation mechanism 3, on an arm with a hydraulic cylinder 4 pivotally mounted, a rod 5, which is kinematically connected with the links of the rotation mechanism (not shown in the figure shown). On the supporting frame 2 pairs of right-handed and left-turning 7 plow bodies are symmetrically fixed in pairs, equipped with uprights 8, bilateral plowshares 9 and dumps 10. The plow bodies are supported by a support wheel, and a block roller 12 with two driveshaft is attached to the frame 2 using a cardan shaft 11 Hooke's hinges, one of which 13 is attached to the supporting frame 2, and the second 14 to the frame of the support-leveling roller, which is made in the form of a frame on which batteries of needle 15 and knife 16 disks are sequentially mounted with the drive and driven sprockets, respectively. On the front linkage 17 of the tractor, a hopper 18 is fixed for applying mineral fertilizers.

To optimize the parameters of the multifunctional arable unit (MAU), we have developed a mathematical model that takes into account dump plowing with simultaneous additional crumbling, leveling the soil and applying mineral fertilizers.

A set of scientific methods for solving problems of managing organizational systems is an independent scientific field, which took shape as a study of operations [9]. Its purpose is a quantitative substantiation of decisions made, the best of which is called optimal. Operational research consists of the following stages - setting a problem, building a mathematical model, solving a problem, analyzing a solution, implementing a solution in practice.

In the study of operations, the most difficult and crucial step is the selection of a decision criterion - in our case, this is the minimum of the total energy consumption for the implementation of the plowing work process with the simultaneous application of mineral fertilizers. The minimum value of these costs determines the correct decision-making.

Operations research is performed on constructed process models using simulation. A model is an abstract construction, an intermediate link between theoretical and abstract thinking and objective reality. The model reproduces the studied object or process in a simplified form, but should adequately reflect reality. By modeling we understand the study of the original not directly, but indirectly using an artificially constructed system called the model. Modeling includes the process of building, studying and applying models.In mathematical modeling, the model reproduces the basic relationships and patterns of the original in mathematical form. In our case, for MAU, these are the dependences of the required tractor engine power on the implement's working width, its mass and the weight of the attachment to the plow, as well as the regularities of the unit's performance on the working speed, working width and coefficient of use of the shift time, the dependence of the specific fuel consumption on engine power, totality of MAU energy costs from its parameters and operating modes (optimization criterion).

Statement of the problem for constructing a mathematical model of optimization.

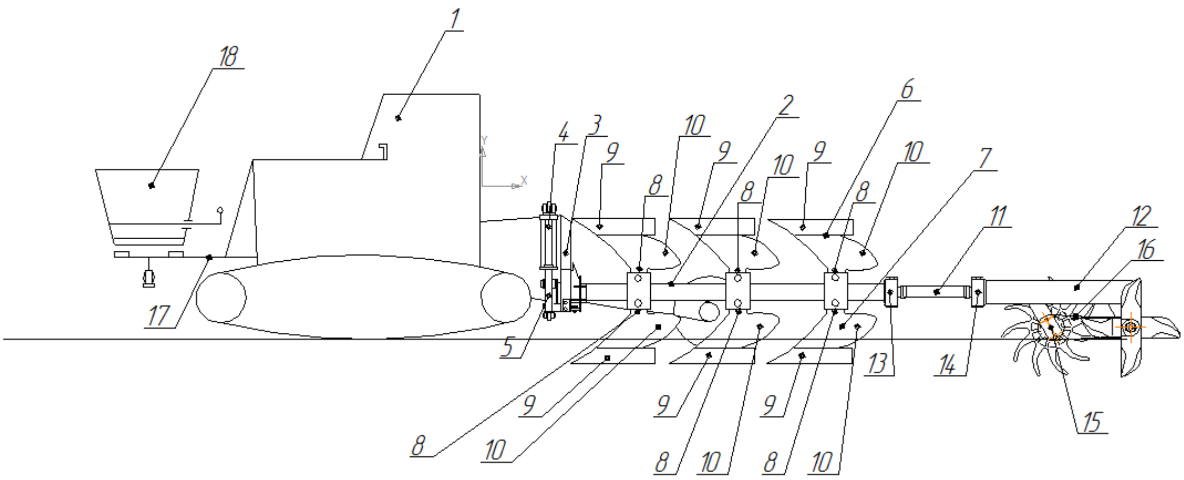

Fig. 1. Multifunctional unit for tillage and fertilizing

It is about determining the optimal parameters and operating mode of the MAU. In this problem, the unknowns are: tractor engine power, its mass, MAU working width, operating speed of the unit, specific fuel consumption, productivity. As a result of the solution, it is necessary to find the indicated parameters and the optimization criterion - a minimum of the total energy expenditures for the implementation of the plowing processes with simultaneous main fertilizer application. The goal of the task is to provide a process with minimal total energy consumption.

Formalization of the task.

At this stage, determine which parameters of the simulated system must be reflected in the model. The model should only have a mathematical description, not a verbal one. This will allow you to get an accurate result when solving on a computer. Each characteristic in the model is reflected using an interval and a number: B_p - a given interval of the working width of the MAU from 0.6 m to 6 m, step 0.6; unit operating speed range $V_o = 7-10\ km/h$ (step 1) coefficient of use of the shift time τ = 0.8; tractor engine power Ne; tractor weight G_{tr}; weight MAU G_{MAU}; unit productivity W, ha / h; total energy consumption for plowing E_z, MJ / ha; tractor annual load $T_G^T = 900h$; annual load MAU $T_G^M = 240h$; the norm of deductions for depreciation, repair and maintenance of the tractor a_{rt} = 0.193 and MAU a_{rm} = 0.38.

Development of a mathematical model of the problem and its recording in structural form.

The mathematical model of our problem means a special scheme in which all technological design, operational, economic parameters, as well as production conditions and requirements are expressed in the form of equations and inequalities and combined by the objective function (Fig. 2).

The sequence of development of the model: first, they make up a system of variables, then a system of constraints, and at the end, a target function. Distinguish between primary and secondary variables. The main ones are introduced into the model, what needs to be determined: N_e, G_{tr}, G_{MAU}, W, B_p, V_p, E_z. Auxiliary variables are introduced into the model if, using the main variables, it is impossible to formalize all the conditions of the problem:

$q_T = 0{,}144 N_e$ - specific fuel consumption MAU, kg / h.

Constants: l_T = 42 MJ / kg - energy equivalent of fuel; a_r - depreciation; T_g - annual load of the tractor and MAU.

Coefficients: 0.1 - conversion factor when calculating the unit hourly output ($W = 0{,}1 B_p V_p \tau$).

After recording the system of variables, a model constraint system is developed:

$$B_p \le 6m; \quad V_p \le 10\ km/h; \quad N_e \le 380\text{kw}; \quad G_{tr} \le 20t; \quad G_{MUA} \le 6t$$

The order in which the model is written in structural form.

As a criterion for optimizing the mathematical model in our task, we took the minimum of total energy expenditures for the implementation of the process of plowing the soil with the simultaneous application of mineral fertilizers by the multifunctional arable unit (MAU). The objective function of the model is expressed by the following equation (1):

$$E_z = \{E_g + \frac{G_{TR} l_{TR} a_{rt}}{T_G^T} + \frac{G_{MUA} l_m a_{rm}}{T_g^M} + \quad ,(1)$$
$$+\left[1 + 0{,}1(G_{TR} - 3500) + 0{,}1(G_{MUA} - 3000)\right]\} / W \to \min$$

where E_z is the specific total energy consumption for the process, MJ / ha;

E_g - energy costs of living labor, MJ / ha;

G_tr is the mass of the tractor, kg;

l_{tr} is the energy equivalent of energy consumption per 1 kg of tractor mass, MJ / kg;

l_m - the energy equivalent of energy consumption per 1 kg of the weight of the agricultural machine, MJ / kg;

aRT, arm - deductions for depreciation, repair and maintenance, respectively, of the tractor and the aggregated machine;

T_G^T, T_G^M - annual load, respectively, of tractor and machine, h;

G_{MAU} - weight MAU, kg;

W – MAU productivity in 1 hour of shift time, ha / h;

The energy costs of living labor E_g are determined by the well-known formula:

$$E_g = l_g n_s + l_g' n_s', \quad (2)$$

where l_g, l_g' - energy equivalents of living labor costs, respectively, of the main and auxiliary workers, MJ / h;

n_s, n_s' - the number of main and auxiliary workers, people

Development of a block diagram of an algorithm for optimizing the parameters and operating modes of the MFU.

To calculate the mathematical model on a computer, we developed an algorithm whose block diagram is shown in Figure 2.

The block diagram includes six arithmetic operators (2-7), one logical (9), the first one for inputting the initial data, and the ninth one for printing the calculation results with the minimum value of the optimality criterion E_z.

The first operator introduced the intervals of the working width B_p capture MAU (0.6-6 m) in increments of 0.6 m, working speeds $V_p(7-10\ km/h)$ in increments of 1 km / h, annual tractor loading $T_g^T = 900h$ and cars $T_g^M = 240h$, depreciation rates for repairs and maintenance of the tractor a_{rt} (0.193) and agricultural machinery a_{rm} (0.38), as well as the values of all the necessary coefficients for the functioning of the mathematical model: l_{tr}, l_m, l_t, l_g, 0.162.

The first operator, having processed the initial data, transfers control to the second arithmetic operator, which, on the basis of the approximation, derives the dependence of the tractor engine power N_e on the working width of the implement B_P and transfers control to the third arithmetic. In the third operator, the dependence of the tractor mass G_{tr} on the working width is formed, and in the fourth, also based on the approximation, the dependence of the MAU mass on its working width is obtained taking into account the mass of the reversible plow and devices for applying fertilizers, additional crushing and leveling the soil.

The fifth arithmetic operator, having received control from the fourth, calculates the productivity of the arable unit for 1 hour of shift time, using the initial data (block 1) and the coefficient 0.08, as the product of the coefficient τ - the use of shift time (0.8) and the conversion coefficient 0 , 1 when calculating unit performance. The formula assumes the constant value of the coefficient τ. Its dependence on the headland, working speed, working width and loading time of mineral fertilizers will be specified in the future.

The sixth arithmetic operator, using the dependence of N_e on B_P, calculates the hourly fuel consumption of the tractor (kg / h) and transfers control to the seventh to calculate the objective function E_z.

After calculating the source data for all arithmetic operators, the control receives the eighth logical one, in which all calculations and the use of the source data are checked.

Next, the eighth operator transfers control to the ninth, which prints out the calculation results with the minimum value of the optimization criterion: N_e, G_{tr}, G_{MAU}, W, B_p, V_p, T_g^T, T_g^M, and also provides information on all intermediate values of the total energy expenditures E_z to build a dependency graph. After that, the ninth operator gives a command to stop the machine.

Record restrictions.

The limitation of the working speed of the movement of the arable unit is selected taking into account the capabilities of energy resources produced by the industry.

Accepted speed range $V_p = 7-10\ km/h$ suitable for the interval of tractor engine power 40 - 420 kW, depending on the working width of the machine. All of the parameters listed are given in the block diagram of the task optimization algorithm:

$$B_p \le 5{,}4m; \quad V_p \le 10\ km/h; \quad N_e \le 420kW;$$ Formulas of unit
$$G_{tr} \le 14800kg; \quad G_{MUA} \le 4860kg$$

productivity and hourly fuel consumption Gp after transformations will take the form:

$$W = 0{,}08 B_p V_p \tag{3}$$

$$G_{tr} = 0{,}162 N_e \tag{4}$$

III. RESULTS AND DISCUSSIONS

The solution of the optimization problem for substantiating the parameters of the proposed MAU (Fig. 2) made it possible to determine the working width and weight of the machine, the speed of movement, the required engine power and the mass of the tractor for aggregating MAU, as well as the optimal MAU productivity for 1 hour of main time and the value of the optimization criterion - minimum total energy costs for plowing with fertilizer (table. 1).

Table - I: Optimal parameters of the MAU

#	Options of MAU	Parameter Values
1	Working width, m	5,4
2	Working speed, km / h	10,0
3	Tractor engine power, kW	303
4	Tractor weight kg	11465
5	Weight MAU, kg (plow + roller + hopper)	8071
6	Optimum productivity MAU, ha / h	5,4
7	Minimum total energy consumption	779,0
8	per process, MJ / ha	900,0
9	Tractor annual load, h	240,0

From the presented data of the results of modeling the MAU workflow according to the developed algorithm (Fig. 2), it follows that in order to obtain the minimum energy consumption of the plowing process with related technological operations (779 MJ / ha), the proposed MAU with a working width of 5.4 m, an operating speed of 10 km / h, tractor engine power 303 kW, unit productivity in one hour of main time 5.4 ha.

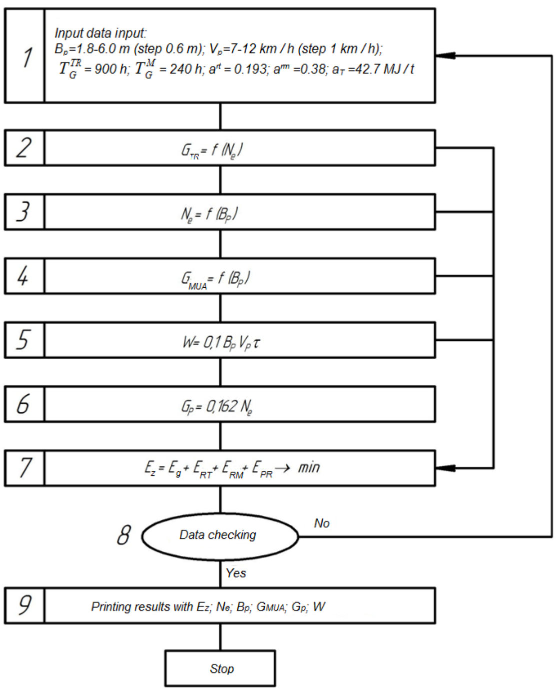

Fig. 2. Block diagram of the algorithm for optimizing the parameters and operating modes of the MAU

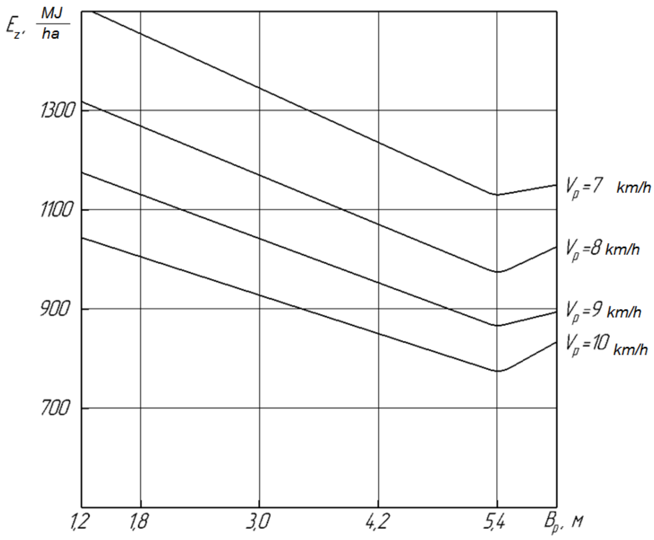

Fig. 3. The dependence of E on B_P and υ_p

Unit productivity increases with increasing values of υ_p and capture width B_p (Fig. 4).

Unit productivity is calculated by operator 5 of the flowchart of the algorithm (Fig. 2).

The dependence of the optimization criterion for the minimum total energy consumption E on the working width B_p and the driving speed υp is shown in Figure 3. The minimum criterion takes place on the working width of 5.4 m and the speed of the unit 10 km / h. The lower the speed of the unit, the higher the cost of the specific energy consumption of the plowing process due to the low productivity of the unit.

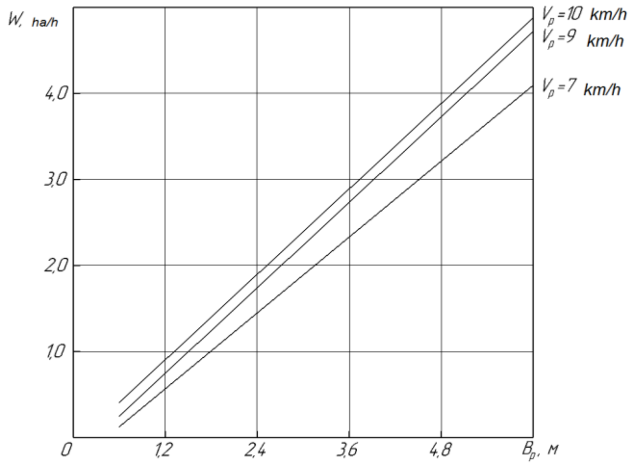

Fig. 4. Dependence of W on υ_p and B_p

Using the approximation method, we obtained the dependences of the tractor engine power for aggregating the proposed MAU (Fig. 5)

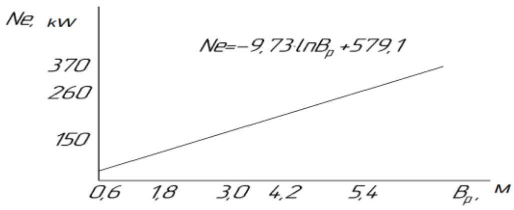

Fig. 5. The dependence of the tractor engine power on the working width MAU

The resulting mathematical model in Fig. 5 is checked for adequacy by the Cochren criterion. The calculated value of G_p = 0.262 and it is less than the tabular (theoretical) G_T = 0.788.

Approximate dependences of the tractor mass on the engine power (Fig. 6) and the MAU mass on its width (Fig. 7) were also obtained.

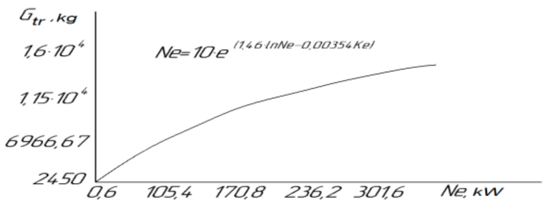

Fig. 6. The dependence of the mass of the tractor on engine power

The mass of the required tractor for the unit also naturally increases with the growth of its engine power (Fig. 6). For MAU with an engine with a power of 105.4 kW, the mass is 6245.0 kg, and with an engine of 236 kW it is 10,800 kg, and for 367 kW it is 14,800 kg.

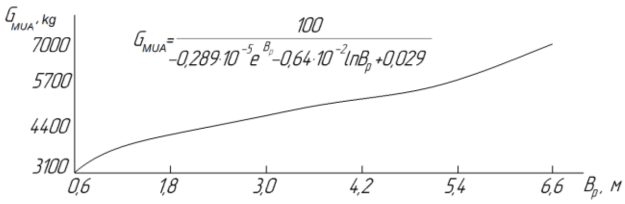

Fig. 7. Dependence of the MAU mass on its width

The mass of the proposed MAU multifunctional arable unit is determined by its three components: the mass of the reversible plow, the mass of the fertilizer spreader mounted on the front linkage of the tractor (Fig. 1) and the mass of the plow adaptation for additional crushing and leveling the soil. With an increase in the width of the machine, the width of the devices and their mass also increase.

The dependence of the MAU mass on the working width of the unit has the form:

$$G_{\text{MAU}} = \frac{100}{-0,289 \cdot 10^{-5} \cdot e^{B_p} - 0,64 \cdot 10^{-2} \cdot \ln B_p + 0,029}$$

The reliability of the obtained dependence is also verified by the Cochren criterion. Its calculated value C_p = 0.311 is less than the tabular (theoretical) S_t = 0.788, which indicates the adequacy of the model.

All three obtained dependencies were used by us in the development of a mathematical model for optimizing the parameters and operating modes of the multifunctional arable unit (MAU), intended for the main application of mineral fertilizers simultaneously with plowing with a reversible plow.

For the composition of the proposed MAU, we used reversible plows [2]. Their advantage was already noted above, but among them you can choose a more effective one. We made an analysis of the technical characteristics of various plow designs [2, 10] and identified the most effective one (Table 2).

An analysis of the data presented in table 2 allowed us to state that the most effective plow among those compared in table 2 can be attributed to PSHKO - (5 + 1 + 1) x60. With 8 cases on the frame, it provides the largest working width (4.8 m), while the PPO plow - (8 + 2 + 1) x40P - with 22 - only 4.4 m cases. More than twice the PPO - (8 + 2 + 1) has a mass, and, consequently, a metal consumption. Even with conventional plows, presented in table 2, PSHKO plow has a lower specific gravity, only 715 kg per 1 m of working width. Such advantages are provided by the plow body design without a field board (Fig. 8).

Table - II: Comparative characteristics of plows of various technological schemes

Mark of plows	Design and performance					
	working width, m	weight kg	specific gravity, kg / m	specific productivity	productivity ha / h	number of cases, pcs
Rotary plow PPP - (6 + 1 + 1) x45	3,6	3020	838,9	1,0	3,6	8
Reversible plows: PPO-8-40П	3,2	6000	1875	1,0	3,2	16
PPO-(5+1+1)x40P	2,0	3230	1615	1,0	2,0	10
PPO-(8+2+1)x40P	4,4	8760	1991	1,0	4,4	22
PSHKO-(5+1+1)x60	4,8	3430	715	1,0	4,4	8
Conventional Plows: PNU-6-35	2,1	1720	819	1,0	2,1	6
PP-(9+2)x35P	3,85	4210	1094	0,96	3,7	11

Fig. 8. General view of the body of the plow PSHKO - (5 + 1 + 1) (Russia)

The advantages of the PSHKO plow also provide them with economic efficiency. Unfortunately, at present, these plows are not yet provided with the devices we offer above, which reduces their effectiveness.

A low specific gravity also has a rotary plow PPP- (6 + 1 + 1) x45 Svetlograd plant (Russia). It also has 8 buildings [10], but is significantly inferior in terms of working width and productivity to the reversible plow PSHKO- (5 + 1 + 1) x60 (Table 2). There are substantial reserves to increase performance indicators for the PPP- (6 + 1 + 1) x45 rotary plow.

Ways to solve this problem are to increase the width of the plow and reduce the weight of the hulls.

Thus, analysis of the effectiveness of various designs of dump plows and multifunctional aggregates allows us to formulate new directions for increasing their efficiency: the transition to multifunctional arable aggregates combining the technological operations of plowing, fertilizing, additional crumbling and leveling the soil behind the plow; transition to the construction of Russian plow bodies without a field board; to select the optimal composition of a multifunctional arable unit, taking into account operating conditions, use mathematical modeling according to the proposed algorithm and mathematical model.

IV. CONCLUSIONS

The requirements of a scientifically based farming system for the main tillage are determined by the creation of MAU [1], capable of performing several technological operations in one pass across the field: dump plowing, applying basic mineral fertilizer, additional crumbling of the soil layer and leveling its surface behind the plow. This combination of operations in one pass of the unit, taking into account the original design of plow bodies and additional devices, increases the efficiency of multifunctional arable units, improving the quality of plowing, reducing costs and energy consumption of the soil cultivation process. In addition to protecting plants from weeds by sprayers [11-13], plowing with dump plows is also effective. Different designs of dump plows give different values of technical and economic indicators, but the best of them is provided by a tractor of traction class 5 and a reversible plow with working dump bodies without field planks and with devices for basic fertilizing, additional crushing and leveling the soil. Using the presented mathematical model, the parameters and operation mode of the proposed MAU are optimized.

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