

METHOD OF JUSTIFICATION FOR PARAMETERS OF TRACTOR-IMPLEMENT UNIT WITH REGARDS TO THEIR IMPACT ON CROP PRODUCTIVITY

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Abstract. Topicality of the research: the value of the research is caused by the need to optimize main parameters of an agricultural tractor during its operation, taking into account their influence on the crop and the actual absence of such optimization methods. Purpose of the study: the purpose of the work is to develop an energy-based mathematical model of a tractor-implement unit (later – ‘unit’) to identify the optimal parameters of the tractor, the width of the implement and the speed of the unit, which increase the efficiency in terms of energy costs. Research methods: the main research method is mathematical modeling based on system analysis, field experiments and computational simulations. Results of the research: the paper describes the proposed structure of the system under study, a justified criterion for optimizing the tractor parameters, and some interdependencies of the proposed energy-based mathematical model parameters. As a result of use of the theory of similarity and the organization of six-factorial experiment, dependence of the maximum pressure of a wheel of the tractor on the soil is received. It is revealed that with increase in the wheel size, the width of its profile decreases in a vertical load on the wheel, the maximum pressure of the wheel on the soil decreases. It is found that in the structure of total energy costs the major part is accounted for by the energy of the crop lost due to the impact of machinery and the optimality of the unit parameters (from 40 to 80 % depending on the type of operation, equipment used, operating conditions of units). Value: the proposed method of optimization of the main parameters of the tractor and unit will be useful in justifying the mass of the tractor and the power of its engine, both at the design stage of tractors and operations. The practical use of the research results benefits in a reduction of the total energy costs. The magnitude of reducing energy costs depends on the used tractors, agricultural machines and the conditions of their operation.

Keywords: tractor, unit, optimization, parameters, energy, mathematical model, harvest, losses.

1. Introduction

The sustainable development of agricultural business implies, along with other principles, also a continuous increase in labor productivity. In order to increase labor productivity in agriculture highly powerful tractors are supplied. With the increase in the traction power of the tractor, the issue of its effective operation becomes topical. The efficiency of the use of tractors and tractor-implement units on the basis of tractors depends on the features of the technological operation, the size of the fields, the optimality of the parameters and operation modes (both of the tractor and the tractor-implement unit as a whole) [1-17]. Previous researchers noted in their works that when optimizing the parameters of agricultural machinery, including tractors, it is necessary to use a systematic approach, to take into account the influence of parameters and operating modes of the technology on the final result of production – the yield of the cultivated crop [18-21].

It is also believed that for forecasting calculations, it is undesirable to use optimization criteria based on monetary units, because they are highly subject to subjective processes inherent in the financial environment [22-24]. The criterion of optimization should be complex, objective, synthesizing and consistent with the system under consideration, i.e. comprehensively describe it. It should allow to obtain optimal values of the parameters of the technology, which retain their stability for a sufficiently long period of time. Such a criterion can be the total energy costs per unit of work performed by the tractor and its implements [25].

This article proposes a scientific experimentally verified method for selecting a tractor with optimal basic parameters (tractor mass and engine power), and optimizing parameters (working widths) and operating modes (operating speed) of the tractor-implement units (TIU) on their basis, both at the design stage and at the stage of operation.

The peculiarity and novelty of the method is connected with the criterion of optimizing the parameters and operating modes of the tractor and the unit as a whole.

A substantiated criterion for optimizing the parameters of aggregates is most fully correlated with the crop formed through crop losses due to improperly chosen parameters of the technology.

The research task is to reduce both direct and indirect energy costs and energy losses through grain.

2. Materials and methods

2.1. Methodology and methods of the research

The methodology accepted for the conducted research is based on the positions of system analysis [26]. The construction of system models relies on the intensive development of information technology. The main element of the system model is the formal system, which, unlike ordinary mathematical models – which are a set of equations, often based on the use of some mathematical apparatus, – includes various mathematical and logical modules, from which they create an algorithm for solving the problem. For tractor-implement units, the formal system is composed of the applied mathematical apparatus of the theory of engines, theory of tractors, operation of the tractor and implements fleet, empirical dependencies obtained using the theory of similarity, methods of mathematical statistics.

This also includes techniques, programs and algorithms that allow to calculate the effectiveness of the system – say, to determine the energy or monetary costs of the tractor-implement unit per unit of the work performed. Optimization of the parameters of the tractor and sowing unit is based on the use of numerical methods.

The scheme of studies using the system homeostatic model is shown in Fig. 1. Some features of system studies of machine-tractor aggregates follow from the following circumstances [26].

- The TIU system study assumes, starting with item 7 in Fig. 1, continuous refinement of the system model of sowing units, iterative studies and infinite in time approach to truth.
- Systemic studies suggest a constant refinement of the system model of units on the basis of experimental studies. The program, goals and tasks of experimental research are based on theoretical studies and computational experiments.

2.2. Purpose of the study

1. To justify the optimization criterion and develop an energy-based systematic mathematical model of the seeding machine to optimize the main parameters of the tractor, the width of the seeder and the moving speed of the unit, taking into account their influence on the crop.
2. To solve the problem, possible system variants and performance indicators of these systems and their elements that can be considered to achieve the stated goals and objectives of the study are analyzed – see Fig. 2 [27; 28]. The system of tractor-tool-operator-operator-field-soil-harvest (TTOFSH) was chosen as an object of the research. It was revealed that the more complex the system under consideration, the more generalizing, systemic, and complex should be the system's efficiency index in order to include all the partial indicators of the effectiveness of elements and subsystems of a complex system. This indicator is the total energy costs, which, in addition to direct and indirect energy costs, include, as an element, the energy of the crop lost due to the choice of not optimal tractor and TIU parameters.

The scheme for revealing the structure of the optimization criterion is shown in Fig. 3. To obtain the maximum energy output, when operating a tractor-implement unit, it is necessary to obtain the maximum yield with minimal energy costs. The maximum yield will be obtained, if we comply with the technological requirements for the performance of the technological operation – we carry out adjustments of the agricultural implement according to the instructions for their operation and observe the speed regime that ensures the required quality of the work performed. Therefore, the condition $[V]_{\min} \leq V_p \leq [V]_{\max}$ must be observed – the unit speed should not exceed the limits allowed by the technological requirements for the quality of the operation. This is the first limitation in the future mathematical model of the TIU. In addition, the value of the grown crop depends on the loss of the potential crop due to the violation of the technological terms of the technological operation and the negative impact of the tractor wheels on the soil. The crop losses can be reduced by optimizing the parameters and operating modes of the MTA, as well as a combination of direct and indirect energy costs.

The second limitation in the future mathematical model of the TIU is based on the fact that the required power N_e for the operation of the TIU should not exceed the rated power of the engine N_{en} , and the slip of the tractor wheels δ should be within the permissible range $[\delta]$, i.e.

$$N_e \leq N_{en}, \delta \leq [\delta].$$

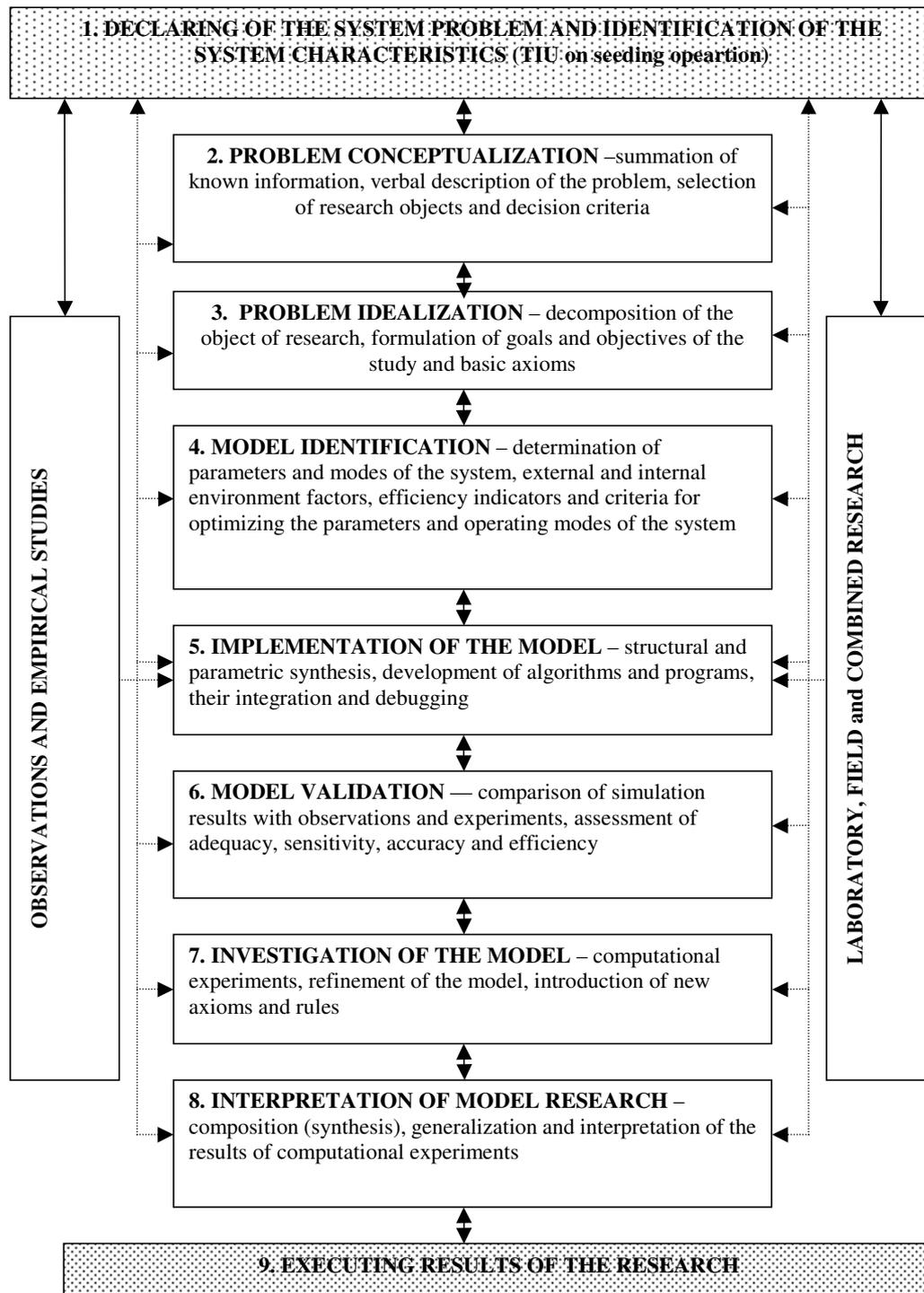


Fig. 1. Scheme of conducting system studies of machine and tractor units on sowing

The energy criterion for optimizing the parameters and operating modes of the tractor and TIU on seeding as a whole will look as follows [25]:

$$E = E_{m.tr} + E_{m.imp} + E_{rts} + E_{u.c.} + E_{drv} + E_{fo} + E_{agr} + E_{exp} \rightarrow \min, \tag{1}$$

where E – specific total energy expenditure, $\text{MJ} \cdot \text{ha}^{-1}$;

$E_{m.tr}$, $E_{m.imp}$ – energy spent, respectively, for the manufacture of a tractor and agricultural machine, per 1 hectare, $MJ \cdot ha^{-1}$;
 E_{rts} – energy spent on all types of repair and technical service of a tractor and agricultural implement, $MJ \cdot ha^{-1}$;
 $E_{u.c.}$ – energy spent on assembling and disassembling the seeding unit, $MJ \cdot ha^{-1}$;
 E_{drv} – energy spent by the machine operator on the control of the unit (turning, stopping and starting and shifting gears), $MJ \cdot ha^{-1}$;
 E_{fo} – energy spent for fuel, $MJ \cdot ha^{-1}$;
 E_{agr} – energy of the crop lost due to a violation of the technological terms of the technological operation, $MJ \cdot ha^{-1}$;
 E_{exp} – energy of the crop lost due to soil compaction by the tractor wheels, $MJ \cdot ha^{-1}$.

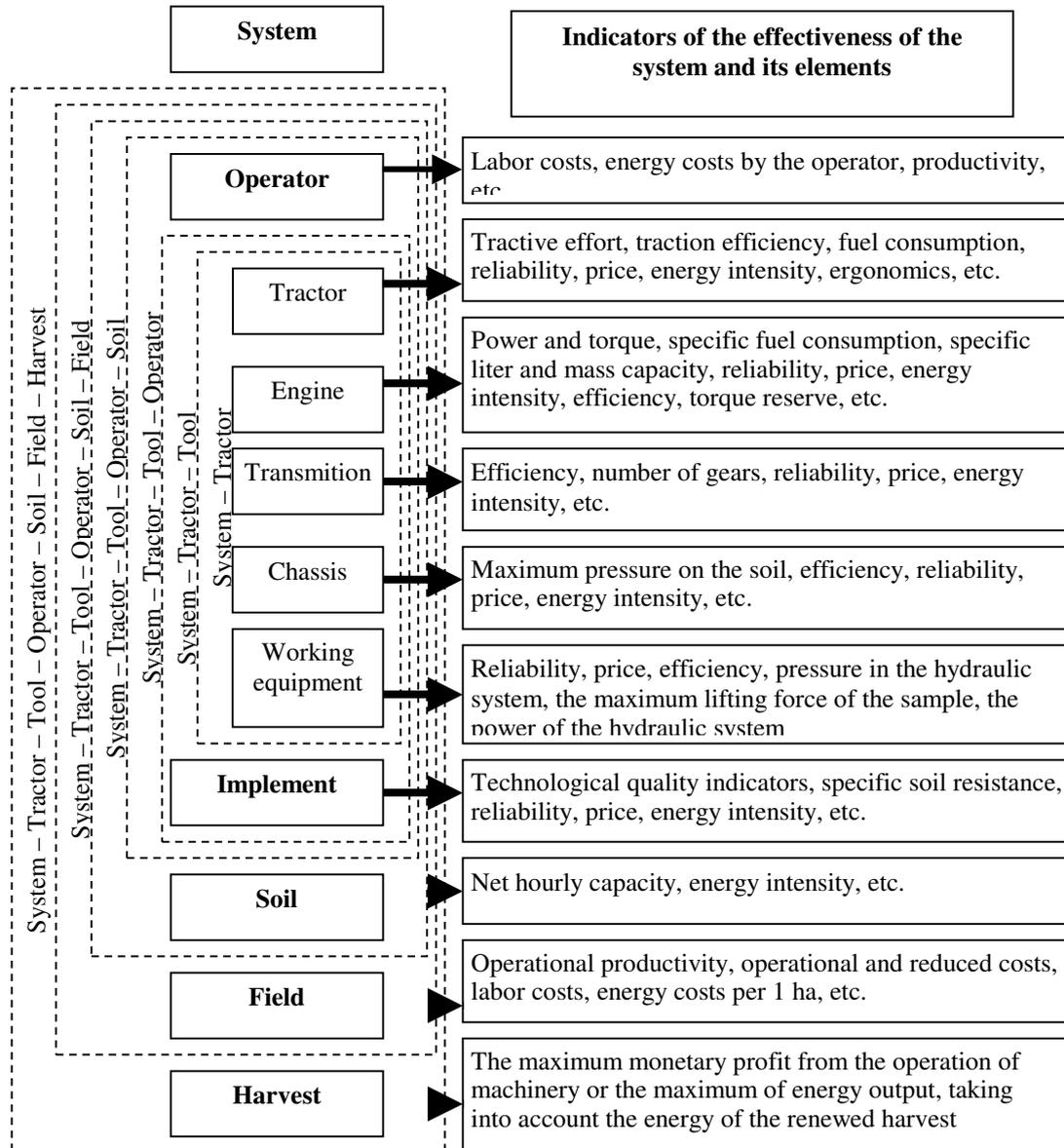


Fig. 2. Possible variants of studied systems and indicators of effectiveness of systems and their elements

The problem of constructing an energy-based system mathematical model is reduced to determining the dependence of each component of the total energy costs (1) (modules) on the main parameters of the tractor and the unit. To date, there are no calculation methods and corresponding mathematical models to optimize the main parameters of the tractor (the mass of the tractor and the power of its engine), taking into account their influence on the crop formed. The compilation of such

systematic energy-based mathematical model of the TIU for optimizing the main parameters of the tractor will have a novelty and practical significance.

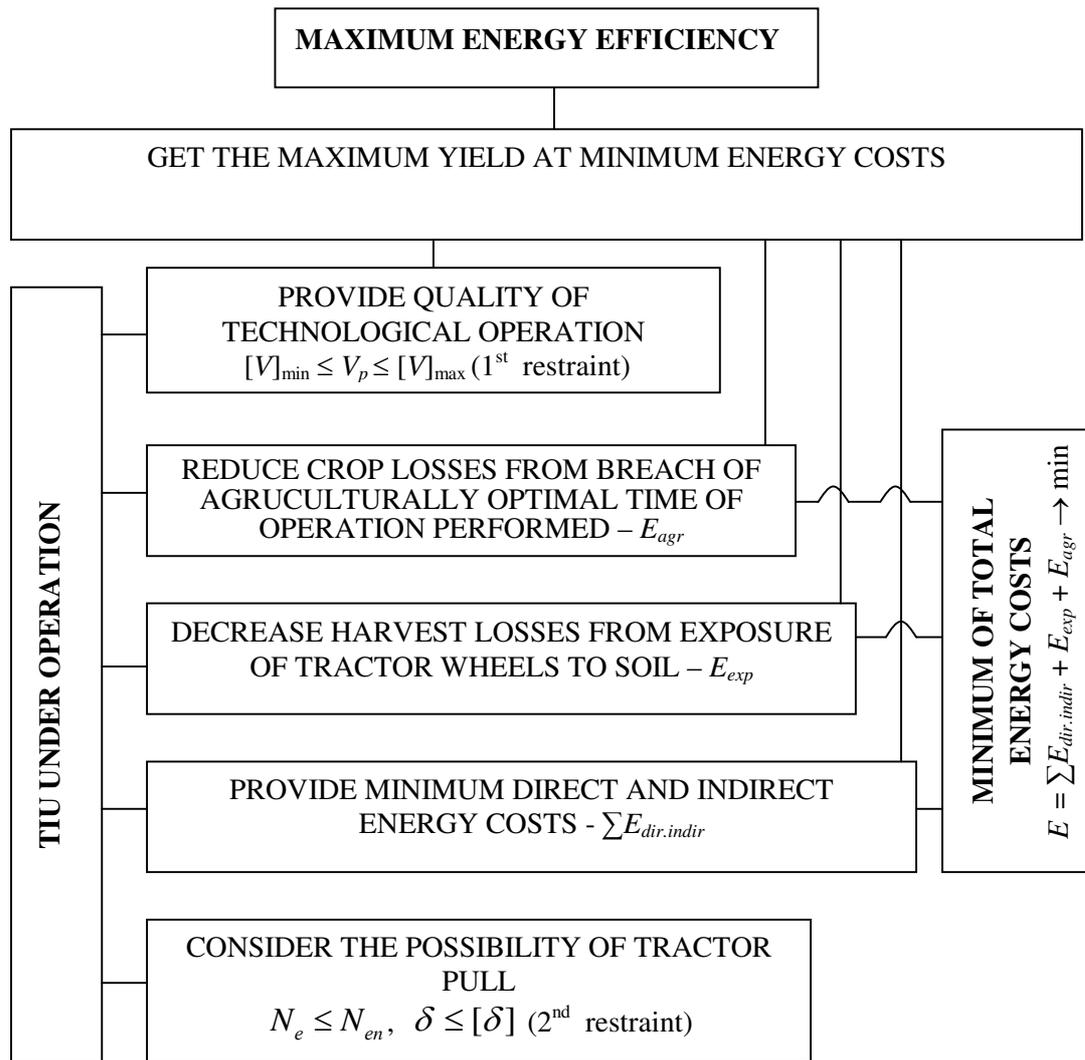


Fig. 3. Scheme to determine criterion of optimization for tractor and TIU main parameters

3. Results and discussion

The procedure for calculating the components of the total energy costs of $E_{m.tr}$, $E_{m.imp}$, E_{rts} , $E_{u.c.}$, E_{drv} , E_{fo} is given in [24].

Errors in choosing a tractor, parameters and operating modes of sowing units lead to crop losses. The loss of crops from violation of the agro-operation is determined by the following model (2), (3), (4) [24]:

$$E_{agr} = \frac{\sum_{i=1}^{N_i-1} (\tilde{N}_L i W \dot{O}_{sh} n_{sh}) + (N_i + 1) \Delta i C_L W_{sh} \dot{O}_{sh} n_{sh}}{S_0}, \tag{2}$$

where C_L – yield loss coefficient, MJ·ha per day⁻¹

$$C_L = Y \Delta y Q / 100, \tag{3}$$

- where Y – planned yield, kg·ha⁻¹;
- Δy – loss of crop in % for 1 day of violation of the optimal operation timings;
- Q energy intensity of 1 kg of product (grain), MJ·kg⁻¹;
- N_i number of whole days in N_1 (4);

Δi – residual incomplete day in N_1 ;
 S_0 – volume of work per season, per one seeding unit, for this operation, ha;

$$N_1 = \frac{S_0}{W_{sh} T_{sh} n_{sh}}, \quad (4)$$

where N_1 – number of days required to perform the operation on the area S_0 ;
 n_{sh} – coefficient of shifts;
 T_{sh} – duration of shift, hours.

To calculate the energy of the crop lost due to compaction of the soil, we use the equation [23]:

$$E_{exp} = A Y Q \left(\frac{B_1}{2B_p} \sum_{j=1}^n w b_k q_{max} + [U] \cdot \left(1 - \frac{n B_1}{2B_p} \right) - [U] \right) / 100, \quad (5)$$

where A – coefficient determining the percentage of lost crop per unit of sealing action of tractor wheels, $\% \cdot m \cdot kN^{-1}$;
 Y – planned yield, $kg \cdot ha^{-1}$;
 Q – energy intensity of 1 kg of product, $MJ \cdot kg^{-1}$;
 B_1 – width of the impact zone of the compacting effect of the tractor on the yield of crops on the field (in the approximate calculations $B_1 = 10.8$ m);
 B_p – working width of TIU, including the given tractor, m;
 n – total number of traces of wheels left by the tractor on the field in one pass;
 w – coefficient, depending on the size and shape of the support surface of the propellers (for wheel propulsion $w = 1.25$);
 b_k – width of the wheel profile, m;
 q_{max} – maximum pressure of an individual tractor wheel on the soil, kPa;
 $[U]$ – permissible level of sealing effect of the tractor wheel on the soil, below which the decrease in the crop yield does not occur = $75 kN \cdot m^{-1}$.

In given model (5), the parameter q_{max} is indeterminate, since it depends on the parameters of the tractor, its wheels and soil properties. To determine the formula for its calculation, experimental studies based on the theory of similarity and planning of multifactorial experiments were carried out. As a result, the equation [29, 30], adequately reflecting the results of other researchers [31, 32]:

$$q_{max} = 3.46\rho_w - 7.4493B\rho_w/D + 0.075552H - 0.23353(\rho_n\rho_w D^3)/M; \quad (6)$$

where q_{max} – maximum wheel pressure on the soil, $N \cdot m^{-2}$;
 D – wheel diameter, m;
 M – mass of the tractor per one wheel, kg;
 B – wheel profile width, m;
 H – hardness of the soil, Pa;
 ρ_n – soil density, $kg \cdot m^{-3}$;
 ρ_w – air pressure in the tires, $N \cdot m^{-2}$.

The simultaneous effect on the magnitude of the maximum wheel pressure on the soil of three factors (6) is shown in Fig. 4.

Data for calculation:

$$\rho_w = 1.6 \times 10^5 N \cdot m^{-2}; H = 15 \times 10^5 N \cdot m^{-2}; \rho_n = 1500 kg \cdot m^{-3};$$

$$[B, D, M] = \text{meshgrid}(0.1:0.0375:0.7, 1.3:0.06875:2.4, 1000:200:4200).$$

The greater the pressure of the wheel on the soil, the more intense the bright red color is the surface of the cube. With a decrease in the diameter of the wheel, the width of its profile and the increased load on the wheel, the maximum wheel pressure on the soil increases.

With the use of the developed energy-based mathematical model of units, computational experiments were carried out to identify the optimal basic parameters of the tractor working in the composition with seeding and tillage units (the results will be given in the following articles). It is necessary to pay attention to the structure of the components of the total energy costs. In the structure of the total energy costs, shown in Fig. 5, the main share falls on the energy of the crop lost due to the

impact of the technology on it and the optimality of the unit’s parameters (from 40 to 80 % depending on the operation, the tractor brand and the agricultural machine). Therefore, in order to obtain objective data, consideration of this component of the optimization criterion is a very important task.

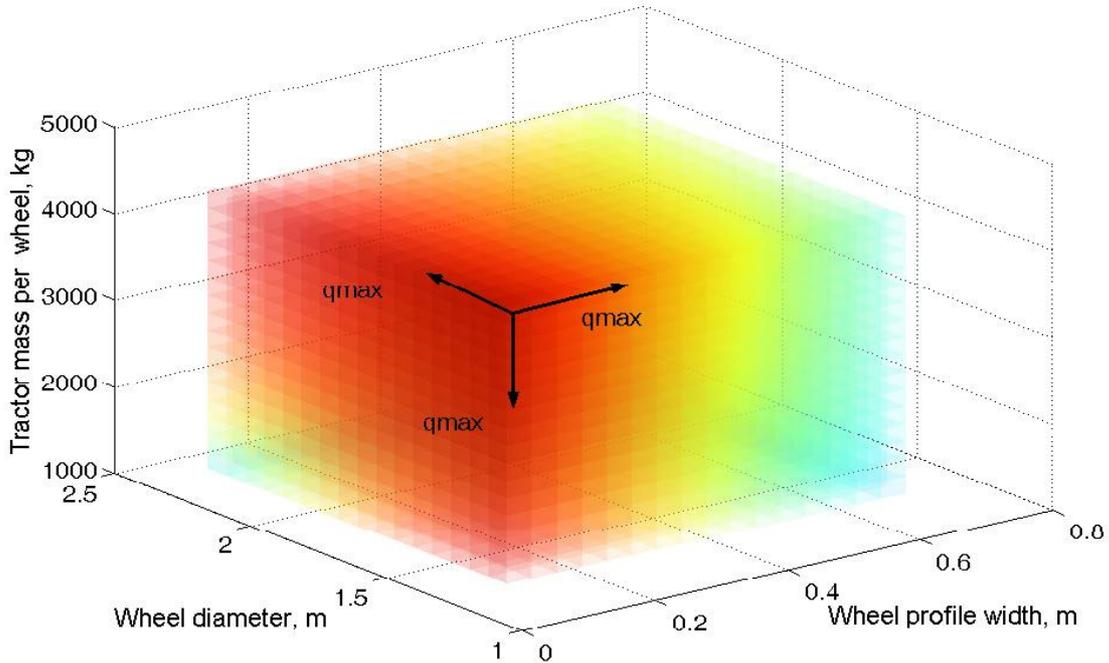


Fig. 4. Change of maximum wheel pressure on soil with change in width of profile, diameter of wheel and weight of tractor per wheel

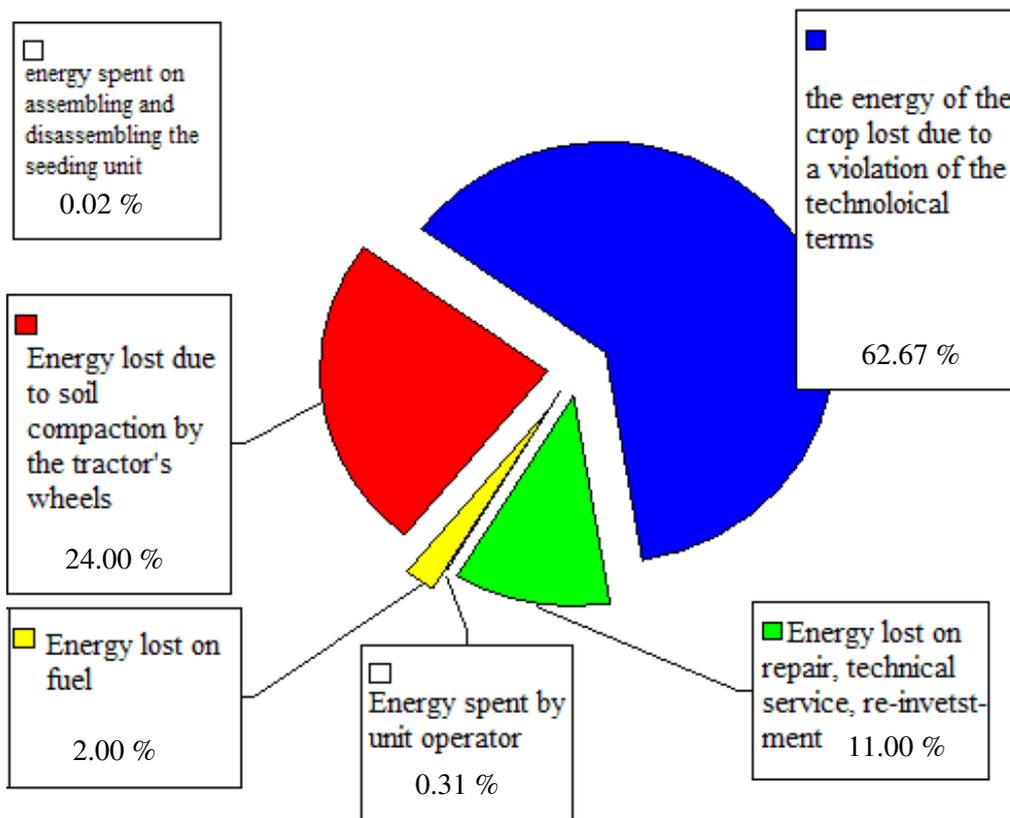


Fig. 5. Example of diagram of ratio of structure components of total energy consumption in crop with crawler tractor

Conclusions

1. The purpose and objectives of the research are formulated in the work. The system of tractor-tool-operator-operator-field-soil-harvest (TTOFSH) was chosen as the object of the research. It was revealed that the more complex the system under consideration, the more generalizing, systemic, and complex should the system's efficiency index be in order to include all the partial indicators of the effectiveness of elements and subsystems of the complex system. This indicator is the total energy costs, which, in addition to direct and indirect energy costs, include, as an element, the energy of the crop lost due to the choice of not optimal tractor and MTA parameters.
2. As a result of using the similarity theory and organizing a six-factor experiment, the dependence of the maximum pressure of the tractor wheel on the soil was obtained. It is revealed that with increasing the wheel diameter, width of its profile, reduction of the vertical load on the wheel – the maximum pressure of the wheel on the soil is reduced. Thus, all equations for calculating each component of the optimization criterion from the parameters of the tractor, aggregate and environmental factors are established and a new methodology for justifying the main parameters of the tractor (tractor weight and engine power), parameters and operating modes of the unit is proposed.
3. It is revealed that in the structure of total energy costs the main share is taken by the energy of the crop lost due to the non-optimality of the parameters and operating conditions of the tractor and the unit – from 40 to 80 %. When optimizing the parameters and operating modes of machine-tractor aggregates, consideration of this component of the energy optimization criterion is a very urgent task.
4. The proposed methodology for optimizing the main parameters and operating modes of the tractor (weight of the tractor and the power of its engine) and the unit (the width of capture and speed) can be used to justify the parameters of the tractor and the unit both at the design stage and at the stage of operation of available tractors and agricultural implements at the enterprises of commodity producers in order to reduce the total energy costs and, in particular, to reduce the amount of lost crop.

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