OPTIMUM WORKING CONDITIONS FOR VARIABLE WIDTH PLOUGHS
/
CONDIŢII OPTIME DE LUCRU PENTRU PLUGURI CU LĂŢIME VARIABILĂ

Cârdei P.[1]; Nuţescu C.*[2]; Matache M.[1]; Cristea O.[1]
[1] INMA Bucharest / Romania; [2] U.P. Bucharest;
Tel: 0727.260.414; E-mail: cristiannutescu@yahoo.com
DOI: https://doi.org/10.35633/inmateh-65-26

Keywords: *variable working width plough, optimal working regime*

ABSTRACT
In this paper, a few assessments of the optimal parametric combinations in the operating regime of agricultural aggregates with ploughs of variable width are made. The starting point was from a classic expression of the tillage draft force required for traction. In order to find optimal points, some problems of constrained extreme have been formulated. Extremes provided by the optimal working width and speed have been found. Such optimal points have existed in the literature, for about half a century. Using these theoretical estimates of the optimal points sought, assessments of the possibilities for their experimental validation were made. Basic conditions for an experimental plan are formulated to highlight such optimal points.

REZUMAT
În această lucrare se realizează câteva evaluări ale combinațiilor optime de parametri în regimul de funcționare a agregatelor agricole cu pluguri cu lățime variabilă. S-a pornit de la o expresie clasică a forței de tracțiune necesară lucrării de arat. Pentru a găsi punctele optimale, am formulat câteva probleme ale extremelor de constrângere. S-au găsit extreme oferite de lățimea și viteza optimă de lucru. Astfel de puncte optimale există în literatura de specialitate, de aproximativ jumătate de secol. Folosind aceste estimări teoretice ale punctelor optimale căutate, se fac evaluări ale posibilităților de validare experimentală a acestora. Sunt formulate condițiile de bază ale unui plan experimental pentru a evidenția astfel de puncte optimale.

INTRODUCTION
With the improvement of the ploughing machines, there has naturally been the concern to optimize their working processes. Such optimization problems are frequently mentioned in the literature (*Dobrescu, 1981; Sandru et al., 1983; Sandru et al., 1982, Stanciu et al., 2011).* The solutions are almost all theoretical in the literature. Experimental research or validation of optimal theoretical solutions are few and incomplete (*Khaffaf A.A. and Khadr, 2008; Deyao Tan, 2015).* Optimal ideas have not changed significantly over time. There has always been the purpose to minimise draft force, power consumption or energy consumed to carry out the work (*Dobrescu, 1981; Sandru et al., 1983; Sandru et al., 1982, Stanciu et al., 2011).*

In the field of use of the tillage machines, ideas were expressed regarding the optimal moisture for soil tillage, and regarding the problem of increasing the working speed in order to increase productivity. With the development of the variable working width ploughs (the end of the seventh decade of the past century), besides working speed, the working width has become another important optimization parameter (*Adel El Titi, 2003; Cronk et al., 1987).*

Researchers have used various approaches to predict the draft force, using analytical and numerical methods *(Almaliki et al., 2018).* Some dynamometers measure all force components acting on the implements. In some other designs, only the horizontal and vertical forces are measured (*Mohammadreza A.-G., et al., 2020*). The obtained characteristics make it possible to optimize the structural and technological parameters of the working parts of machines using computer simulation *(Mudarisova S.G., et al., 2019).* The predictions from one proposed artificial neural network (ANN) model were very satisfactory, based on comparisons with other reported results using multiple linear regression and the mean absolute errors between the measured and predicted values using the ANN model were 0.99 kN and 2, respectively, 39 kWh / ha *(Abdulrahman A.-J., et al., 2020).*

The conclusions presented by *Shafaei S.M., et al., 2019* can contribute both to academic knowledge and to practical applications to properly manage the energy indices of the tractor during soil tillage operations to optimize energy consumption and dissipation in tillage systems.

Also, researches regarding optimum working conditions for tillage equipment (ploughs, shears, loosening equipment) were carried out in the period 2007-2016 by numerous researchers, who studied:

- utilization of ante-mouldboard in the construction of ploughs *(Biriş S.Şt. et al., 2007)*,
- soil particles' kinematics during the ante-mouldboard tillage tools working process *(Biriş S.Şt. et al., 2008),*
- stress distribution determination appearing on the lamellar mouldboard surface with a view to modelling and optimization *(Bungescu S. et al., 2008),*
- nonlinear friction and resistance, generating sources of optimal points in the energy field of agricultural aggregates working process *(Cârdei P. et al., 2013),* respectively
- determination of the subsoiler traction force influenced by different working depth and velocity *(Croitoru Şt. et al., 2016).*

MATERIALS AND METHODS

Possible objective function and components of the objective functions

For optimal calculus, it was started from a well-known form of the plough draft force – V.P. Goryachkin's equation. Equation (1) describes the traction (draft) force mathematically:

$$F = f \cdot G + n \cdot k \cdot ab + n \cdot \varepsilon \cdot ab \cdot v^2 \tag{1}$$

where: F is the draft force, f is a coefficient of friction between metal and soil, G is the plough weight, n is the number of plough mouldboards, k is a coefficient that characterizes the specific deformation resistance of the soil, a is the working depth, b is the mouldboard working width, ε is a coefficient that depends on the surface of the mouldboard active shape and on the soil properties, and v is the working speed.

It is considered that the working speed is constant and the expression of the power consumed for traction is obtained, using the following formula:

$$P = F \cdot v \tag{2}$$

Let's assume that the conditions are fulfilled so that the energy required for the tractor to trail the plough on a surface with area A, is given by the following formula:

$$E = F \cdot L = F \frac{A}{n \cdot b} \tag{3}$$

The theoretic productivity (the real productivity, which includes the turns and other working specific times, will be considered in a later stage) is considered in the working process:

$$W = n \cdot b \cdot v \tag{4}$$

Taking into consideration that without adding some additional conditions (restrictions) to the basic formulas from which it was started, the chances of finding extreme local points are very small or null (*Al-Janobi A.A. and Al-Suhaibani S.A., 1998*; *Cârdei P. et al., 2013*), the productivity as value, *W,* was set constant, and then from relation (4) the working speed can be expressed:

$$v = \frac{W}{n \cdot b} \tag{5}$$

Introducing (5) in (1), the following form of the draft force is obtained:

$$F = f \cdot G + n \cdot k \cdot ab + \frac{\varepsilon \cdot a \cdot W^2}{n \cdot b} \tag{6}$$

The function F from (6) depending on the working width *b*, has a positive extremum point, which is characterised by the following coordinates:

$$b_{opt} = \frac{W}{n}\sqrt{\frac{\varepsilon}{k}}, \quad F_{opt} = f \cdot G + 2 \cdot a \cdot W \sqrt{k\varepsilon} \tag{7}$$

which is a minimum point for the function F from (6).

A similar solution can be obtained, using the working speed, v, similarly expressed by (5):

$$b = \frac{W}{n \cdot v} \tag{8}$$

Operating just like parameter v, for function (1), the optimal point is obtained, having the following coordinates:

$$v_{opt} = \sqrt{\frac{k}{\varepsilon}}, \quad F_{opt} = f \cdot G + 2a \cdot W \sqrt{k \cdot \varepsilon} \tag{9}$$

For power function (2) and energy function (3), there were no optimal points obtained (or optimal points of their own have negative coordinates, which does not have any physical sense in the studied process).

Also, as objective functions, to optimize working speed or working width (considering that a variable working width plough is used), other functions, such as the *draft force specific to the unit of productivity* f_w, can be considered:

$$f_w = \frac{F}{W} = \frac{fG}{n \cdot b \cdot v} + \frac{k \cdot a}{v} + \varepsilon \cdot a \cdot v \tag{10}$$

The power required for traction, specific to the unit of productivity

$$p_w = \frac{P}{W} = \frac{fG}{n \cdot b} + k \cdot a + \varepsilon \cdot a \cdot v^2 \tag{11}$$

and *the mechanical energy specific to the productivity unit, required for plough traction:*

$$e_W = \frac{E}{W} = \frac{A}{n^2} \left(\frac{fG}{b^2 v} + \frac{nka}{bv} + \frac{n\varepsilon av}{b} \right) \tag{12}$$

The objective function (10) has an optimal point (minimum) only in relation to the working speed with the coordinates:

$$v_{opt} = \sqrt{\frac{k}{\varepsilon} + \frac{fG}{n \cdot \varepsilon \cdot ab}}, \; f_{wopt} = \sqrt{\frac{\varepsilon \cdot a}{n \cdot b}} \left(f \cdot G + n \cdot k \cdot ab \right). \tag{13}$$

The objective function (11) has no optimal points in relation to variables b or v. The objective function (12) has an optimal point (minimum) only in relation to the working speed v:

$$v_{opt} = \sqrt{\frac{k}{\varepsilon} + \frac{fG}{n \cdot \varepsilon \cdot ab}}, e_{wopt} = \frac{2A}{n^2 b^2} \sqrt{n \cdot \varepsilon \cdot ab \left(f \cdot G + n \cdot k \cdot ab \right)}. \tag{14}$$

RESULTS

The main results prove that there are optimal points in the working process of the unit formed by tractor and the variable working width plough. In addition, the optimal points found have as abscissa not only the working speed but also the working width, a control parameter defining this type of ploughs, which according to (http://www.ploughmen.co.uk/about-us/history-of-the-plough), were introduced at the end of the 1970s. There are also other points of view regarding the optimization of working width for ploughs for which this parameter is adjustable. One is suggested in (*McKyes E., 1985*) and the term energy efficiency is introduced. In addition, the optimality criteria used are natural, meaning intuitive.

From a physical point of view, the parametric structure of the coordinates of the optimal points leads to interesting conclusions, facilitated by the fact that these coordinates were found in the analytical and not numerical way. They confirm the optimal points, in terms of working speed and working width, found from reference works in the field of agricultural machinery exploitation (*Al-Janobi A.A and Al-Suhaibani S.A, 1998; Almaliki et.al., 2018; Biriş S. et. al, 2007; Biriş S. et. al, 2008*).

Analytical results

In concrete terms, the assertions about the obtained results refer to the coordinates of the optimal points given in (7), (9), (13), and (14).

It is noted that of the four optimal operating points found, only one has as abscissa an optimal working width, which minimizes the draft force (6) in the conditions of a fixed productivity (5). The same draft force, with the same productivity, is achieved with the optimal speed from (9).

It is interesting that the two optimal points (7) and (9) lead to the same expression of the minimum draft force. This means that the two optimal conditions (can be ascertained by calculation) are fulfilled simultaneously. The optimal common speed of the optimal points given in (13) and (14) minimizes the power and power functions specific to the unit of productivity.

It should be mentioned that the optimal speeds are characterized by a quantity that will be noted as a critical process speed:

$$v_{cr} = \sqrt{\frac{k}{\varepsilon}} \tag{15}$$

The critical speed (15) is equal to the optimal speed given in (7) and (9), and the optimal speed given in (13) and (14), can be written as in the following formula:

$$v_{wopt} = v_{cr}\sqrt{1 + \frac{f \cdot G}{n \cdot k \cdot ab}} \tag{16}$$

From (15), it results that the square of the critical speed, v_{cr}, is the ratio of constants describing the soil structure, k and ε. Optimal speeds (16) differ from critical speed v_{cr}, through the ratio of the frictional force to the static component of the traction resistance.

According to the data from (Letosnev M. N., 1959), for the usual values of the k and ε model constants, the critical speed is limited in the range between 2 m/s and 9 m/s. The optimal speed that minimizes the power and energy specific to the productivity unit (16) is greater than the critical speed that minimizes draft force, (9).

It should also be noted that the critical speed, v_{cr}, is also included in the expression of the optimal working width (7).

Numerical results

In order to facilitate a wider understanding of the possibilities of optimal choice of working regime for variable working ploughs, as considered in this research, some numerical results in the specific case of a variable working width plough are presented.

A variable working width plough equipped with n = 3 mouldboards, with a mass of 600 kg, working depth set at 0.3 m, working width between 0.15 m and 0.45 m (to better highlight the optimum value) was considered. Soil characterized by the parameter values f=0.45, k= 25000 Pa, ε= 1992 kg/m^3 was considered.

To obtain the curves of figures 1 - 4, a value of W=1.08 ha/hour (3 m^2/s) for productivity was used and A=1 ha, the surface for energy calculation, was considered.

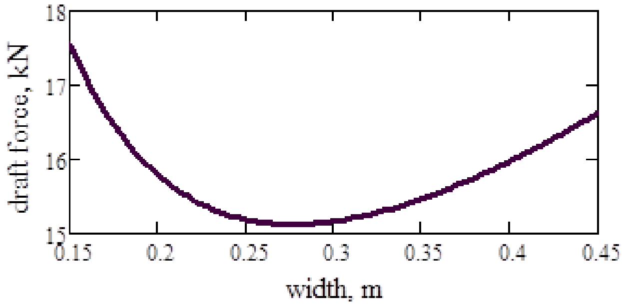

Fig. 1 - Optimum point of the *draft force* in relation to the working width

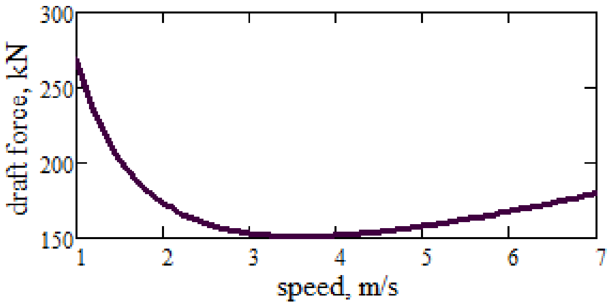

Fig. 2 - Optimal point of the *draft force* in relation to the working speed

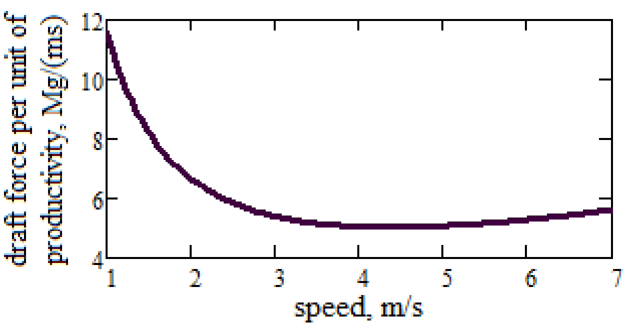

Fig. 3 - Optimum point of the *draft force specific* to the unit of productivity, in relation to the working speed

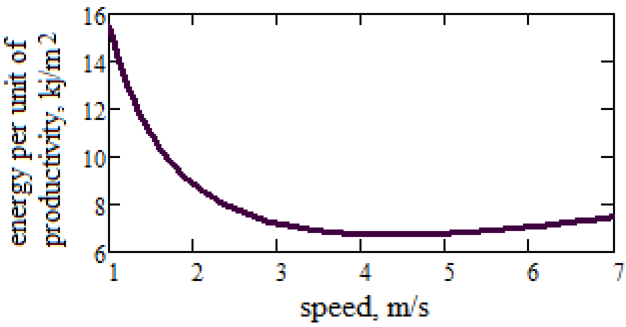

Fig. 4 - Optimum point of the *energy required for traction, specific to the productivity unit*, in relation to the working speed

It can be seen that the numerical study materialized in the curves in figures 1 - 4 confirms the theoretical results, both qualitatively and quantitatively.

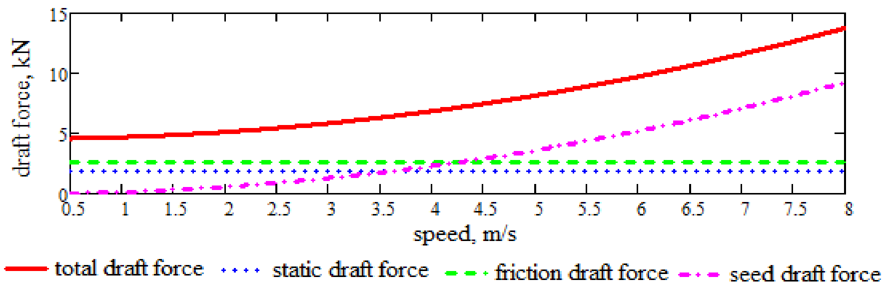

Fig. 5 - Dependence of draft force and its components on the working speed

It can be seen that for the numerical case analysed in this paper, at working speeds higher than 3.5 m/s, the component of the draft force dependent on the working speed, gradually exceeds each of the other components. At working speeds higher than 4 m/s, this component becomes dominant. At a working speed of 5.7 m/s, the total draft force doubled due to the speed dependent component, and at the speed of 8 m/s tripled. In such experiments, in which all the power of a tractor with a large reserve of power was used, there were cases of failure of the plough bearing structure.

As a result of these observations, it is useful to include a structural verification of the plough's resistance in the experimental plan providing high intensity tests. The complexity of designing a load bearing structure of the plough also results, considering the high traction capabilities of modern tractors, as well as some deficiencies in operation (failure to observe working speed limitations). Practically, having very powerful traction means, it is often important to finish soil works as quickly as possible so that the aggregate is used at the maximum tangible speed.

CONCLUSIONS

- Without complicated numerical analysis, it is noted that both the optimal working width, the b_{opt}, or the optimal working speed, the v_{opt}, and the objective functions that they minimize, depend on the parameters that encapsulate the intrinsic environment, k, ε and on the interaction parameter between the environment and the working machine: *f*. This dependence expresses that the coordinates of the optimal point vary depending on the soil and implicitly on the meteorological parameters involved.
- The existence of optimal points in the working regime of agricultural machines for soil works is obtained by a classic, very used expression of draft force, (1). The widespread use of this formula, perhaps not the most accurate, is due to its simplicity and physical significance that is easily accepted, although the meaning, is not very well known (the traction force formula (1) is also easy to use in calculating the dynamics of the tractor - plough aggregate).
- In addition, the fact that formula (1) uses only three constants with which it characterizes the soil in the interaction with the machine (*f, k* and ε), is an advantage, considering the tabulation of these values over about one hundred years of use for various types of soils.

- From an experimental point of view, however, literature (at least the wide circulation literature) does not mention the existence of the optimal points that the theory recommends.
- It is obvious that without the experimental validation, the optimal points whose coordinates are given in (7), (9), (13) and (14), remain pure theory. In order to be able to validate these optimal points experimentally, it is necessary to achieve the appropriate experiences. This means that within the variation range of the working width and the working speed of the aggregate, the optimal values predicted by the theory must be included.

$$b_{\min} \le \frac{W}{n \cdot v_{cr}} \le b_{\max} \tag{17}$$

where *bmin* and *bmax* are the minimum working width, and maximum working width achievable by the plough, respectively

$$v_{cr\,\min} \le v \le v_{cr\,\max} \tag{18}$$

are the minimum value, and maximum value of the critical speed value, (15), possible to increase at the minimum and maximum critical speeds (16).

Taking into account the minimum and maximum values of soil characteristic constants, *k* and *ε*, given in the literature, the minimum and maximum values of critical speed (15), 2 m/s and 8 m/s, are obtained. As a result, if speeds of less than 2 m/s are applied, the existence of optimal working speeds cannot be validated. As regards the validation of an optimal working width, this could be observed if the minimum and maximum achievable plough width would have the expressions related to the soil characteristics:

$$b_{\min} = \frac{W}{n \cdot v_{cr_{\max}}}; \quad b_{\max} = \frac{W}{n \cdot v_{cr_{\min}}} \tag{19}$$

From this reasoning, it results the need to include in the experimental plan for the validation of optimal working widths or working speeds, the estimates (17) - (19). Otherwise, it is very likely that validation of such optimal points will receive a (experimental) negative response, although their existence may be a real one.

The realization of the speed regimes necessary for the experimental validation of the optimal working regimes for the variable width ploughs is also conditioned by a very important decision of the experimenter. Increasing the working speed over certain limits leads to increased draft force and strongly stresses the plough bearing structure, which can lead to irreversible damage. Therefore, a plough prepared for such tests must be designed with a sufficiently strong bearing structure (the weight of the plough will increase as well as the optimal type speed (16)).

Investigating the problem of the actual existence of optimal points in the working regime is even more complicated by the fact that the three constants that characterize the soil in (1) depend on the soil moisture and its internal structure (physical and chemical components, layer structure, etc.). If the moisture is well quantified, the physical and chemical structure (component) is deficiently quantified and deeply dependent on depth. The random nature of the physical and chemical structure makes it difficult to be considered in the modelling process. The influence of moisture is quite simple to consider, provided that significant values of this parameter are used. Besides, the existence of optimal working moisture for agricultural machines for soil tillage, has, by long, been supported by specialists, but without giving clear numerical evidence. The introduction of moisture in the optimal calculation makes it necessary to consider the tractor's slippage.

ACKNOWLEDGEMENT

This work was supported by "NUCLEU" Programme, developed with the support of MCID, project no. PN 19 10 01 02.

REFERENCES

[1] Abdulrahman A.-J., Saad Al-H., Abdulwahed A., Almajhadi Y., (2020), Modelling of draft and energy requirements of a mouldboard plough using artificial neural networks based on two novel variables, *Scientific Paper, Agricultural Machinery Management, Eng. agríc. (Online) 40 (3),* https://doi.org/10.1590/1809-4430-Eng.Agric.v40n3p363-373/2020;

[2] Adel El Titi, (2003), *Soil Tillage in Agroecosystems*, CRC Press;

[3] Al-Janobi A.A., Al-Suhaibani S.A., (1998), Draft of primary tillage implements in sandy loam soil, Applied Engineering in Agriculture, *American Society of Agricultural Engineers*, vol. 14(4): 343-348;

[4] Almaliki S., Himoud M.S., Muhsin S.J., (2018), A stepwise regression algorithm for prognostication draft requirements of disk plough, *International Conference on Promotion of Scientific & Regional Cooperation on Food and Agricultural Sciences*, Mashhad;

[5] Biriş S., Vlăduţ V., Bungescu S., Paraschiv G., (2007), Researches regarding the utilization of ante-mouldboard in the ploughs building, *Proceedings of the 35 International Symposium on Agricultural Engineering "Actual Tasks on Agricultural Engineering",* vol. 35, pp 85÷96, Opatija – Croatia;

[6] Biriş S., Maican E., Vlăduţ V., Paraschiv G., Manea M., Bungescu S., (2008), Study regarding the soil particles kinematics during the ante-mouldboard tillage tools working process, *Proceedings of the 36 International Symposium on Agricultural Engineering "Actual Tasks on Agricultural Engineering",* vol. 36, pp. 115÷126, Opatija – Croatia;

[7] Bungescu S., Biriş S., Vlăduţ V., Paraschiv G., (2008), Researches regarding the stress distribution determination appearing on the lamellar mouldboard surface with a view to modelling and optimization, *Proceedings of the 36 International Symposium on Agricultural Engineering "Actual Tasks on Agricultural Engineering",* vol. 36, pp. 281÷292, Opatija – Croatia;

[8] Cârdei P., Alexiou Al., Badescu M., Marin E., (2013), Nonlinear Friction and Resistance, Generating Sources of Optimal Points in the Energy Field of Agricultural Aggregates Working Process, *Conference Proceedings of the 2013, International Conference on Energy, Environment, Ecosystems and Development* (EEED 2013), Rhode Islands, Greece;

[9] Croitoru Şt., Vlăduţ V., Marin E., Matache M., Dumitru I., 2016, Determination of subsoiler's traction force influenced by different working depth and velocity, *15th International Scientific Conference "Engineering for Rural Development", Proceedings*, vol. 15, pp. 817-825, Jelgava, Latvia;

[10] Cronk B. J., Williams, T.H., Krishnan, P., Kemble, L.J., (1987), Optimal width equations for various tillage implements, *American Society of Agricultural Engineers*;

[11] Deyao Tan, (2015), Engineering Technology, Engineering Education and Engineering Management, CRC Press Taylor & Francis Group, p. 436;

[12] Dobrescu C., (1981), Optimization of the parameters of agricultural aggregates to reduce energy consumption, Ministry of Agriculture and Food Industry, *Centre for Agricultural Teaching Material and Propaganda,* Bucharest;

[13] Khaffaf A.A. Khadr, (2008), Effect of some primary tillage implement on soil pulverization and specific energy, *Journal of Agricultural Engineering*, 25(3): 731-745;

[14] Letosnev M. N., (1959), Agricultural machinery, *Agro-Silvica de Stat Publishing House*, Bucharest;

[15] McKyes E., (1985), Soil Cutting and Tillage, Developments in Agricultural Engineering 7, *Elsevier*;

[16] Mohammadreza A.G., Gholamhossein S., Gilandeh Y, Apolonio M., Hernández J.L., Miranda I., (2020), Measuring and comparing forces acting on mouldboard plough and para-plough with wing to replace mouldboard plough with para-plough for tillage and modelling it using adaptive neuro-fuzzy interface system (ANFIS), Agriculture, vol. 10(12), 633, https://doi.org/10.3390/agriculture10120633;

[17] Mudarisova S.G., Gabitova I. I., Lobachevskyb Y. P., Mazitovc N. K, Rakhimovd R. S., Khamaletdinoval R. R., Rakhimoval R., Farkhutdinova A.M., (2019), Modelling the technological process of tillage, *Soil and Tillage Research,* vol. 190, pp. 70-77, https://doi.org/10.1016/j.still.2018.12.004;

[18] Sandru A., Badescu M., Sandru L., (1982), Energy consumption reduction through rational usage of agricultural aggregates, *Scrisul Românesc Publishing House*, Craiova;

[19] Sandru A., Popescu S., Cristea I., Neculaiasa V., (1983), Agricultural equipment exploitation, *Didactic and Pedagogical Publishing House*, Bucharest;

[20] Shafaei S.M., Loghavi M., Kamgar S., (2019), Prognostication of energy indices of tractor-implement utilizing soft computing techniques, *Information Processing in Agriculture* 6(1):132-149.

[21] Stanciu L., Cardei P., Voicu Gh., Vartukapteinis K., (2011), Studies on Optimization of Trailed Corn Harvesting Combines Working Regimes, *INMATEH - Agricultural Engineering*, Vol. 33(1), pp.29-36;

[22] http://www.ploughmen.co.uk/about-us/history-of-the-plough;

[23] https://www.researchgate.net/publication/314154209_Researches_regarding_the_Motion_Equation_of_the_Tractor_in_Aggregation_with_the_Machines_f or_Soil_Processing.