MODELLING THE QUALITATIVE PARAMETERS OF AN AGRICULTURAL AGGREGATE FOR SOIL PROCESSING
/
MODELAREA PARAMETRILOR CALITATIVI AI UNUI AGREGAT AGRICOL PENTRU PROCESAREA SOLULUI

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ABSTRACT
The article presents results obtained in the experimental research of agricultural aggregates intended for soil processing, with special reference to rotary harrows with vertical axis rotor. The authors approach the description of the working process of these machines from a systemic point of view. The general systemic picture is suitable for researching the work processes of many machines and work processes in agriculture and generally in technology, science and technology. Specifically, this approach applies to the aggregate consisting of tractor and rotary agricultural harrow. The efficiency of the results consists in their use in the prediction and optimization of the working process.

REZUMAT
Articolul prezintă rezultatele obținute în cercetarea experimentală a agregatelor agricole destinate prelucrării solului, cu referire în special la grapele rotative cu rotor cu ax vertical. Autorii abordează descrierea procesului de lucru al acestor mașini din punct de vedere sistemic. Tabloul general sistemic este potrivit pentru cercetarea proceselor de lucru ale multor mașini și procese de lucru în agricultură și în general în tehnologie, știință și tehnologie. În mod specific, această abordare se aplică agregatului format din tractor și grapă agricolă rotativă. Eficiența rezultatelor constă în utilizarea lor în predicția și optimizarea procesului de lucru

INTRODUCTION
Mathematical modelling of agricultural aggregates is done in many studies, for example, *Turner et al., (2016), Yisa et al., (1995)*, using systems theory, i.e. the description of the agricultural aggregate as a dynamic system. In agriculture are described systemically the agricultural farms, the management of agricultural farms, agricultural machines, the working process of agricultural machines, the interaction between the environment and the components described systemically and listed before.

Agricultural aggregates are perfectly suited to the systemic description, generally as a very complex system because they are described by a very large number of parameters and many of them have a pronounced random character.

In order to achieve a comprehensive (ideally exhaustive) description of the working process of an agricultural aggregate, a common approach is the mathematical system model.

According to *https://dexonline.ro/definitie/sistem*, the definition of the system that presents interest in this case would be "A set of elements (principles, rules, forces, etc.) dependent on each other and forming an organized whole, which puts the order in a field of theoretical thinking, regulates the classification of a field of natural sciences or makes a practical activity work according to the purpose pursued".

According to *Foley and James, (1996)*, "A system is a complex of interacting elements. It is a unit relatively delimited from the environment, the delimitation being highlighted by the structure and internal connections. The behaviour of a system depends not only on the properties of its components, but also especially on the interactions between its elements". A simple graphical description of the notion of system, an object of study of systems engineering, in this case, is given in *Foley and James (1996)*.

The diagram is reproduced in fig. 1.

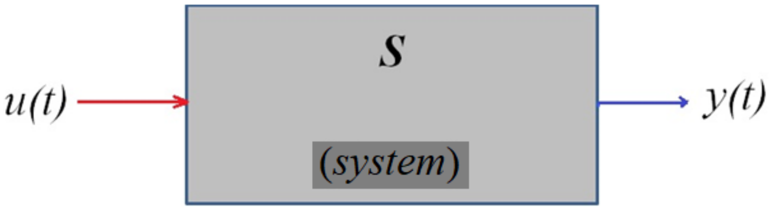


Fig. 1 - Symbolic graphical representation of a system, after *Foley and James, (1996* $t \in \mathbb{T}$.

The vector *u* means the set of causes or input quantities, and the vector *y* means the set of effects or the output quantities. The set of moments of time $\mathbb{T}$ is ordered in the sense that time evolves continuously and uniformly from the past, through the present, to the future. According to *Foley and James, (1996),* between the vectors *u* and *y*, real vectors defined on the set of time $\mathbb{T}$, there is a relation from cause to effect, symbolized by the transfer operator ***S***. In general, the systems are described in mathematical language by mathematical models, the operator of transfer being the relation between the input *u* and the output *y*, translatable by a mathematical relation according to *Foley and James, (1996)*:

$$y(t) = \boldsymbol{S} \circ u(t), t \in \mathbb{T} \quad (1)$$

Where "∘" symbolizes the operation of transforming *u* by ***S*** into *y*.

The mathematical modelling of systems is based on the construction - by systematizing observations, experiments, interpreting measurements and knowing and explaining the general laws of nature - of an image, usually idealized and essentialised, of phenomena in real systems (*Monasterolo et al, 2014*).

This image, having a perfectible form and efficiently usable for knowledge and applications, is the mathematical model.

According to the definition of the notion of a system, the mathematical model is itself a system - an abstract system - through which a real system is represented. Conceptually, the notions of a real system and an abstract system are distinct. They designate distinct entities. The abstract system is an image, more or less idealized and/or simplified, but perfectible, of the real system. The distinction between the real system and its image is illustrated in fig. 2. It highlights the modelling process (accompanied by the identification of structure and parameters) and, implicitly, the role of the systems analyst. It develops the model (EM), designs experiments (EC) - when possible, performs experiments (ESR, ESA), validates the model (VM) based on the error (s) between similar results obtained in ESR, ESA and repeats the procedures CE, ESR , ESA, VM and EM whenever necessary. In this way, it is possible to improve the abstract system following the purposes of mathematical modelling: knowledge, synthesis of structures for monitoring and/or management of the real system, etc.

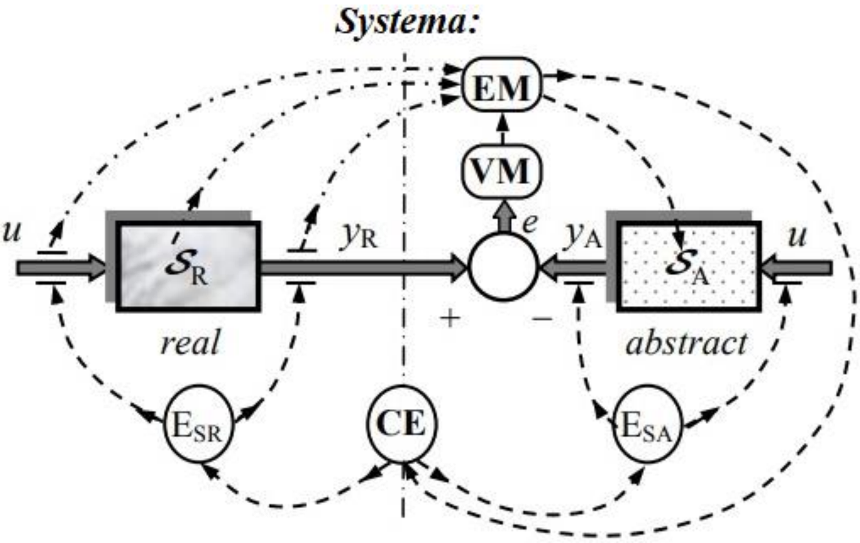


Fig. 2 - The modelling process; $\mathcal{S}_R$ - real system, $\mathcal{S}_A$ - abstract system, u - cause size, y_R, y_A - effect sizes,
$e = y_R - y_A$ - error; EM - model development, CE - design of experiments, E_{SR}, E_{SA} - experiments,
VM - model validation;
-·-·-► – sampling, - - - -► – modelling operations,
(Foley and James, 1996)

From fig. 2 and the explanations above, it is very clear that the experiments must be made only after a minimum mathematical model of the system is sketched so that important parameters are not omitted from the measurement and variation process. Also, in this stage of sketching the model are identified directly measurable parameters, indirectly estimable or those impossible to estimate experimentally.

In research done by *Belea, (1985*), the scheme of the system is a little more complicated than the one given in fig.1, but in some cases more useful.

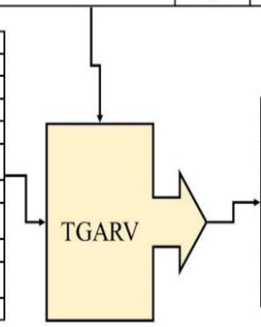
In addition to the systemic description of the GARV (Rotary agricultural harrow with rotors with vertical axis, fig. 3) working process, this article will essentially present the statistical description (by statistical mathematical model) of the qualitative parameters of this aggregate. The statistical description by a mathematical model of some of the qualitative working parameters of any agricultural machine is an important objective because, from their prediction start the improvements in design, the enunciation of possible working regimes (indicating working speed, rotor speed, number of knives on the rotor, depending on the soil structure, its humidity and the required working depth, for example, estimating productivity and consumption) and possible optimizations. In *Iordache et al, (2021),* the experiments performed were described and were presented the statistical methods used to arrive at the formulas for two qualitative working parameters of GARV: fuel consumption and fuel consumption specific to the production unit. The last of the two parameters even has a minimum point for a certain working speed. Also given in *Iordache et al, (2021),* is a formula for the tensile strength as a function of the kinematic index and the number of knives placed on each rotor. It also exposed the variation of the degree of crushing depending on the number of knives, only in terms of the results of descriptive statistics (tabulated data and graphical representations). In this article, inferential statistical results will be given, which complement the results presented in *Iordache et al, (2021).*

MATERIALS AND METHODS

The material of this research is an aggregate consisting of a tractor and an agricultural harrow with a vertical axis rotary (GARV). This aggregate was described in several articles, including those containing experimental results (*Iordache et al, 2021*; *Iordache et al, 2017; Iordache et al, 2020*). This article expands on the area of results presented in *Iordache et al, (2021), Iordache et al, (2020), Iordache and Saracin (2021)*. In addition to the regressions of consumption, it also presents a regression for the degree of crushing, another qualitative parameter of the dynamic tractor-GARV system, output parameter of the system. A systemic (unpretentious) model of the TGARV (Tractor-GARV unit) aggregate is given in fig. 3.

Input parameters: control and adjustment of the working process			
No	**Name**	**Notation**	**Dimension**
1	Rotation speed of GARV rotors	ω	T^{-1}
2	Aggregate working speed	v_l	LT^{-1}
3	Working width	b	L
4	Working depth	a	L
5	The average radius of the rotor blade corresponding to the working depth	r	L
6	GARV mass	M	M
7	MasTractor mass	M_t	M
8	Number of knives on the rotor	n_c	-
9	Number of rotors	n_r	-

Input parameters of the TGARV soil-aggregate interaction process			
No	**Name**	**Notation**	**Dimension**
1	Soil moisture	h	-
2	Average soil density on working depth	ρ_s	ML^{-3}
3	Degree of coverage with plant residues	g_0	-
4	Average resistance of the soil to penetration on the working depth	σ	$ML^{-1}T^{-2}$
5	Soil resistance to deformation, [15]	k	$ML^{-1}T^{-2}$
6	Soil strength factor due to working speed, [15]	ε	ML^{-3}
7	Coefficient of friction between steel and soil	μ	-
8	Rolling coefficient of the tractor wheels with the ground	φ	-
9	Skating of tractor wheels	δ	-



TGARV output process **output** parameters			
No	**Name**	**Notation**	**Dimension**
1	Productivity	w	LT^{-1}
2	Energy consumption	e	$ML^{2}T^{-2}$
3	Soil density a number of days after work	ρ_{sa}	ML^{-3}
4	Resistance to soil penetration a number of days after work	σ_s	$ML^{-1}T^{-2}$
5	Degree of soil shredding after a TGARV pass	G_{m}	%
6	Degree of soil leveling	G_{n}	%

Fig. 3 - A systemic model of the TGARV aggregate

RESULTS AND DISCUSSIONS

The main results of the article belong to the inferential statistics of the experimental data, consisting of interpolation formulas useful for predicting energy consumption, qualitative effects of the work and for optimizing work regimes.

Analysis of the degree of crushing

The experimental data analysed to obtain the interpolation formula of the degree of crushing as a function of forward speed, were determined starting from the surveys of the degree of crushing produced by the passes of the GARV unit with various working speeds, according to the standards for measuring the degree of crushing.

In the calculation of the dependence of the degree of moisture in the soil, depending on the degree of crushing of the soil, the experimental data were presented in the table and represented graphically in fig. 1, the experimental data were exposed in the table and represented graphically in fig. 1.

Table1

Results of measuring the degree of shredding as a function of the working speed of the GARV

Ranges Bulk size of earth, mm	Working speed, km/h		
	0.41	0.52	0.79
<20	39.4	29.3	35.6
20-50	38.1	33.5	29.6
50-80	18.3	21.7	22.0
80-100	8.5	12.2	10.5
>100	1.7	3.3	2.3

Using the data in Table 1, a nonlinear statistical interpolation of the experimental data was performed. The Weibull distribution with two variables was used as the basic dependency force, because of all the known forms, it is considered that it can be closest to the empirical distribution of shredding degree data. It is obvious that the degree of shredding also depends essentially on the number of knives on each rotor. This dependence could not be statistically analysed because the experimental data on the degree of shredding were measured (which is a very time consuming and physically demanding operation) only for equipping with four knives GARV rotators and for a single speed (224 rpm). As a result, a complete dependence on the shredding degree, which includes as arguments the number of knives on the rotor and the speed of the rotors, remains a task for the future research of this machine.

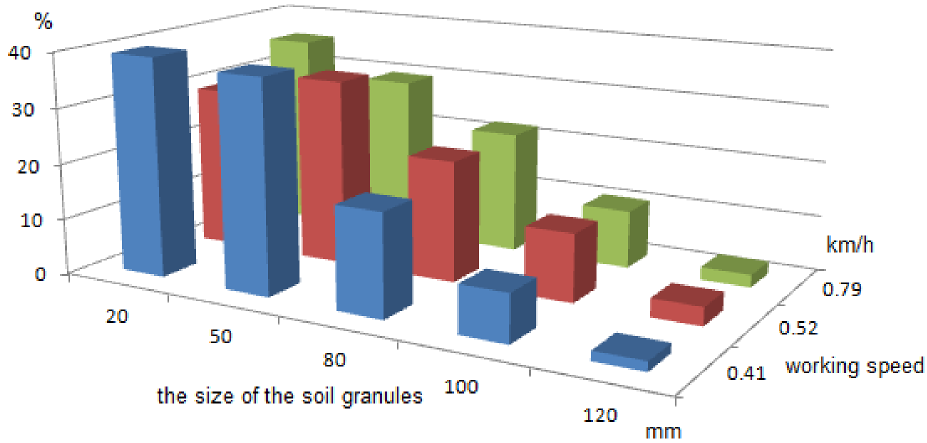


Fig. 4 - Dependence of the degree of crushing (as size - generalized diameter in mm) on the working speed of the unit

Using these experimental data, as well as the nonlinear regression analysis provided by the Mathcad program and theoretically founded in *Montgomery, (2021*) and taking as a basic form the 2-dimensional Weibull distribution, the expression (2) was obtained for the function of the shredding degree whose arguments are the size of the soil granules and the speed of movement of the working unit.

$$G_m(x, v, \alpha_1, \alpha_2, \beta_1, \beta_2, k) = \frac{1}{k} \cdot \left(\frac{x}{\alpha_1}\right)^{\beta_1 - 1} \cdot \left(\frac{v}{\alpha_2}\right)^{\beta_2 - 1} \cdot exp\left\{-\frac{1}{k} \cdot \left[\left(\frac{x}{\alpha_1}\right)^{\beta_1} + \left(\frac{v}{\alpha_2}\right)^{\beta_2}\right]\right\} \quad (2)$$

where x is the size of the soil granules or lumps, v is the working speed, $\alpha_1, \alpha_2, \beta_1, \beta_2, k$, are model parameters.

For the particular case of reddish-brown forest soil, under the environmental conditions specified in the experimental reports, for which the data from table 1 and fig. 4 are presented, the model parameters have the values: α_1=0.033, α_2=1.056, β_1=1.444, β_2=0.889, k=1.844. In fig. 5 is given a 3D graphical representation of the shredding degree function (1), together with the distribution of the experimental points underlying the interpolation calculation (pink dots). A variant of graphical representation of the crushing degree, in the form of a partial function of the size of the soil granules resulting from the processing process, for three working speeds, is given in fig. 6.

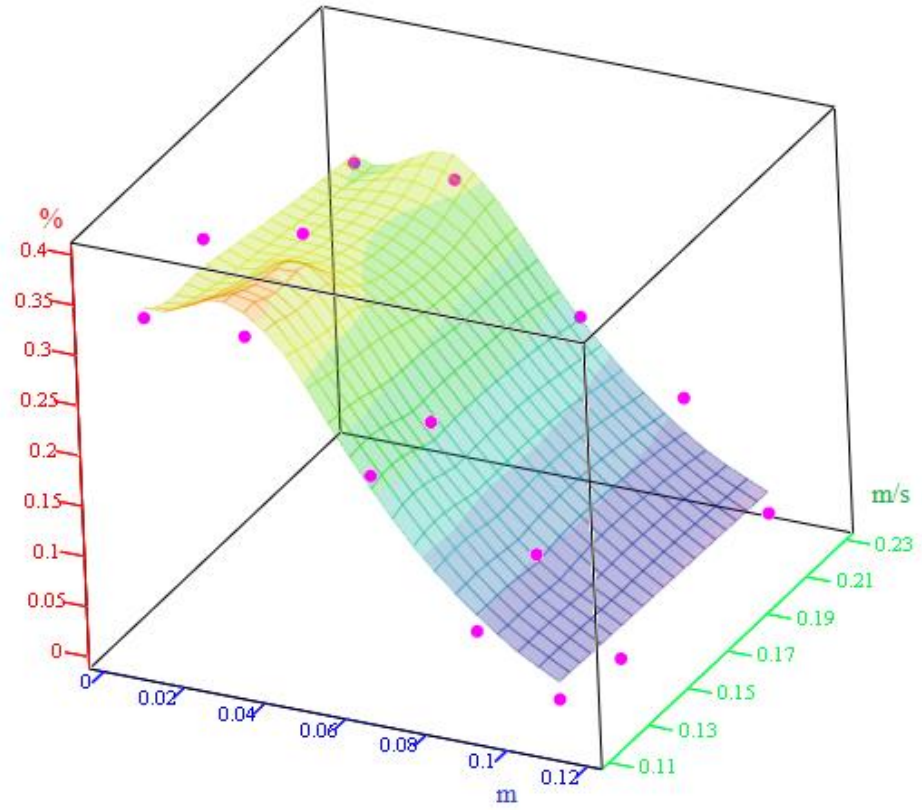


Fig. 5 - 3D graphical representation of the shredding degree function (2), together with the distribution of the experimental points underlying the interpolation calculation (pink dots)

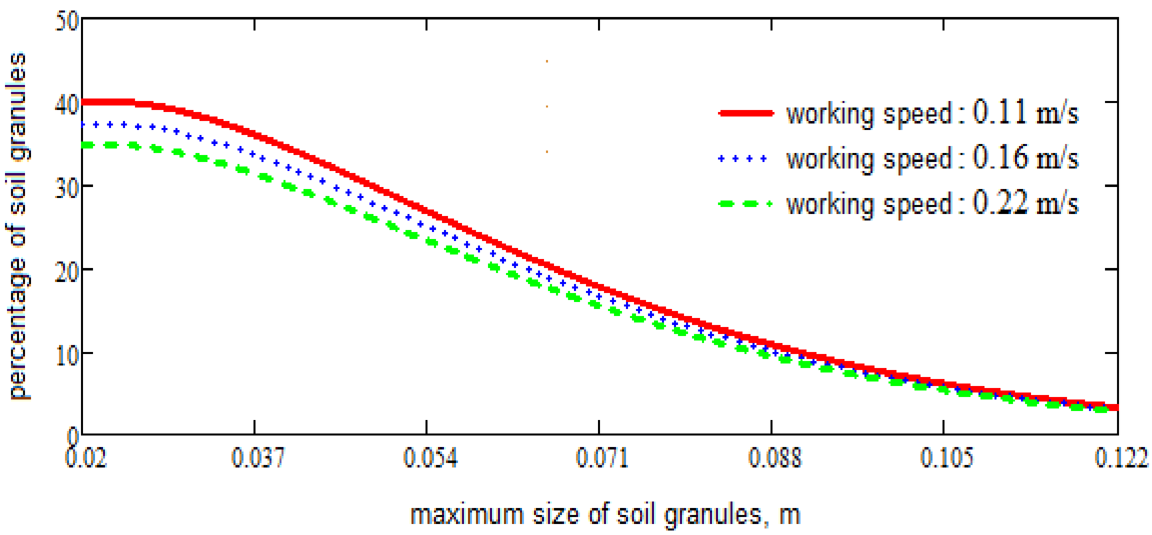


Fig. 6 - Graphical representation of the degree of shredding as a partial function of the size of the soil bulbs, for three values of the working speed

Quality indices of an economic nature

In this chapter, three quality indices of the working process of the tractor-rotary harrow with vertical axis rotors will be studied: fuel consumption, productivity and fuel consumption specific to the production unit. For the estimation of fuel consumption and productivity, only three experiments were performed, the data of which are written in Table 2. Also, in Table 2 are given the productivity and the ratio between fuel consumption and productivity.

Table 2

Economic and energy quality indices for the 224-rpm speed of the car rotors (experimental data)

Working speed km/h	Fuel consumption l/ha	Productivity ha/h	Fuel consumption per unit of productivity, l h/ha^2
0.39	13.8	0.0877	157.265
0.50	14.2	0.1125	126.222
0.77	24.8	0.1732	143.146

Under these conditions, the linear regression equation for fuel consumption is obtained depending on the working speed:

$$C(v) = 0.508 + 30.889v \ \ [\frac{l}{ha}], v \in [0.39, 077] \ \text{km/h} \tag{3}$$

and second-degree polynomial regression:

$$C(v) = 30.662 - 79.796v + 93.744v^2 \ \ [\frac{l}{ha}], v \in [0.39, 0.77] \ \text{km/h} \tag{4}$$

Graphical representations of curves (3) and (4) are given in fig. 7.

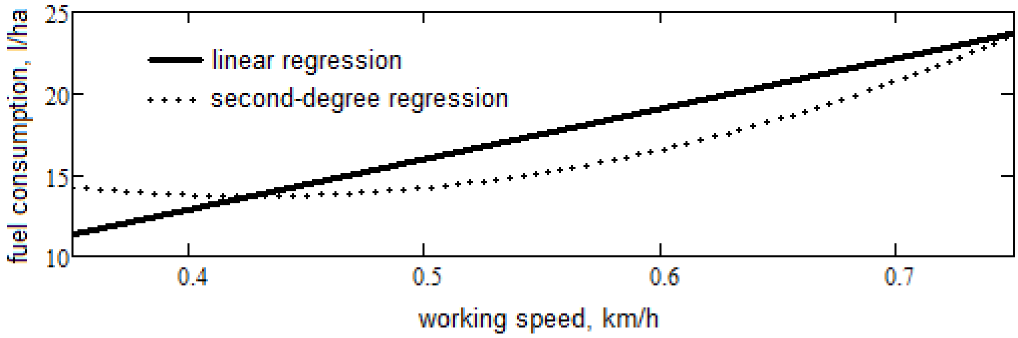


Fig. 7 - Dependence of fuel consumption on working speed, comparison between linear and square regression variants

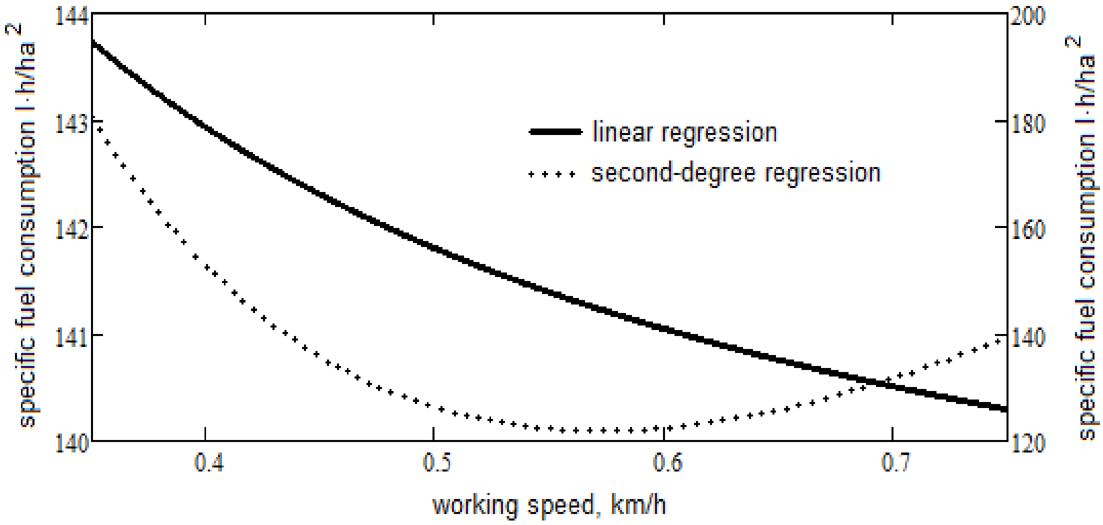


Fig. 8 - The dependence of the consumption specific to the production unit, in two variants corresponding to the modelling of the consumption with the linear or the quadratic regression

The dependence of the specific consumption per production unit, in two variants corresponding to consumption modelling of the with the linear or the quadratic regression, can be expressed as follows.

$$P(v) = 0.225v \text{ [ha/h]},\ v \in [0.39, 0.77] \text{ km/h} \tag{5}$$

Using fuel consumption (variants (3) and (4)), the following are obtained by reporting:

$$C_{sp}(v) = \frac{C(v)}{P(v)} \tag{6}$$

variants of consumption specific to the productivity unit, $C_{sp}(v)$.

The specific consumption of the productivity unit is minimized in order to obtain a higher productivity with a lower consumption. Graphical representations of the relations (3), (4) and (6) are given in fig. 7 and 8. It is observed that only the quadratic variant of regression leads to its own minimum points, optimal for the working regime. For example, the minimum value of consumption, in the quadratic regression variant, is 13,681 l/ha and is achieved at a speed of 0.426 km/h. the value of 0.572 km/h, in this case achieving the lowest fuel consumption specific to the productivity unit, 121,913 lh/ha^2.

In concluding the presentation of this result, two observations are absolutely necessary:

1) The results are particular from two points of view: the environment (especially the soil) on which it was worked and the range of working speed in which it was worked;

2) It is not recommended to extrapolate the results to speeds outside the experimental working range.

Soil tillage draft force

One of the most important energy parameters is the tensile strength at work, because starting from this it can be calculated the power consumed, fuel consumption and other important parameters of the dynamic system GARV. Apart from prediction, the existence of optimal working regimes that minimize the tensile strength, is a constant concern of researchers in the field of agricultural machinery for soil processing and more.

Proceeding according to the same methods of regression analysis, [12], the following expressions of the tensile strength were found, having as arguments the kinematic index of the machine and the number of knives on the rotor or working speed, rotor speed and number of knives mounted on each rotor:

$$R(v, nc, \omega, \lambda) = -23689.74 + 130108.629v + 1573.8nc - 551.307\omega + 476.3\lambda \tag{7}$$

$$R(v, nc, \omega) = -7546.718 + 25081.737v + 1573.8nc + 286.429\omega \tag{8}$$

$$\begin{aligned} R(v, nc, \omega) = {} & 73767.757 - 136356v + 24943.408nc - 10624.518\omega - 4043.833v \cdot nc - 4999.022v \cdot \omega \\ & - 805.574nc \cdot \omega + 856655.311v^2 - 760.0nc^2 + 347.725\omega^2 \end{aligned} \tag{9}$$

where R is the forward resistance force opposed by GARV to the tractor, v is the working speed, (m/s), and nc is the number of knives on the rotor, ω is the angular speed of the rotor (rad/s), and λ, is the cinematic index at GARV:

$$\lambda = \frac{v}{\omega r} \tag{10}$$

Where r is the average radius of the rotor (average radius on the working depth made by the knives), in m.

The Pearson correlation coefficient of the soil tillage draft force of GARV with the parameters considered in this chapter is given in table 3, its size being an indication on the intensity of the connection between the force and that parameter.

Table 3

The Pearson correlation coefficient of the soil tillage draft force of GARV with the independent parameters measured in the experiments described in *Lei F., Yong H., (2005)*

	v	nc	ω	λ
R	0.462	0.587	0.151	-0.266

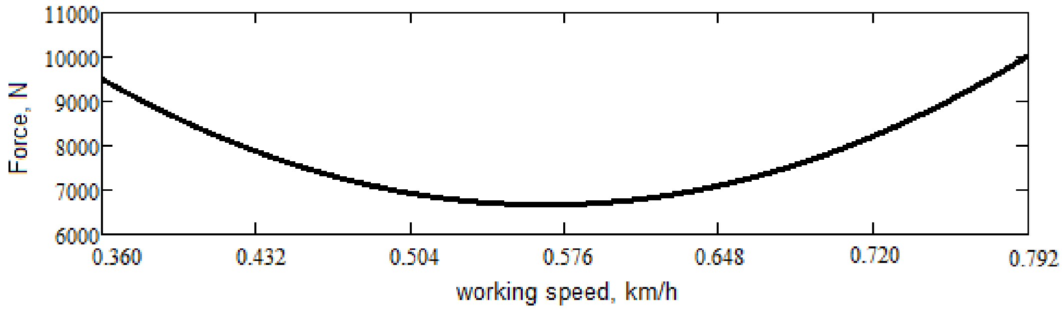


Fig. 9 - The dependence of the soil tillage draft force of the GARV on the working speed, deduced from the experimental data and the date of the expression of the quadratic regression (8), for nc = 4 knives on the rotor, ω = 23.457 rad/s (224 rpm)

In fig. 10 it can be seen how the dependence curve of the tensile strength of the GARV on the working speed varies, depending on the number of knives, for the constant speed, with the value 173 rpm of the machine rotors.

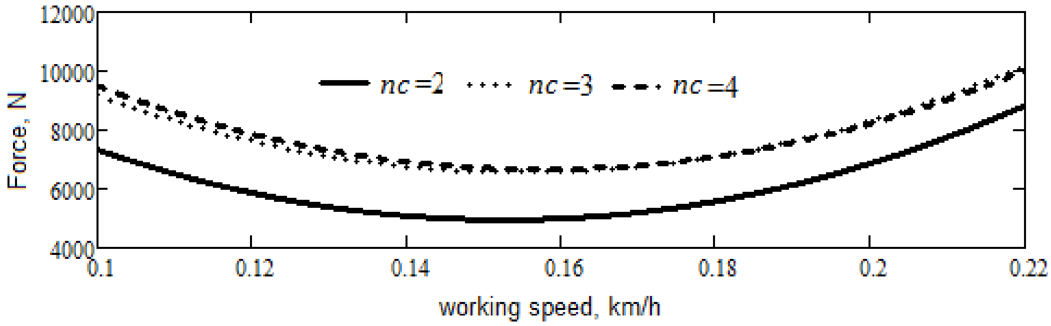


Fig. 10 - Dependence of the tensile strength of the GARV on the working speed, with the number of knives mounted on each rotor, at the value of the rotor speed, ω = 23.457 rad/s (224 rpm)

The conclusion that can be drawn from figure 10 (intuitively expected) is that the soil tillage draft force of the GARV increases with the number of knives mounted on the rotor, but not linearly. There are many in-depth explanations for these results, but they can only be addressed after repeating the experiments and validating the results.

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CONCLUSIONS

An important benefit of experimental research is the statistical models obtained by processing experimental data. Statistical models are mathematical models obtained by interpolation of various types of experimental data. These models complement or correct the theoretical ones. More importantly, statistical models provide relationships between the quality parameters of the work performed by agricultural machines and the input and control (regulation) parameters of the working process. In this way, it becomes possible to optimize the quality, possibly simultaneously with the energy (taking into account environmental aspects) and economic optimization of the working process.

Among the main conclusions of the experimental results are:

- experiments confirm that the working speed and speed of the rotors and the number of knives mounted on each rotor are the main working parameters in the category of control or command parameters, which influence the process;
- the number of knives that equip each rotor is an important parameter in the category of control or command parameters, influencing both the energy of the process and especially the quality of the work performed (degree of crushing and levelling);
- GARV soil tillage draft force increases with the number of knives mounted on each rotor;
- it was possible to obtain mathematical relations (statistical models) of some of the quality indices of the works performed by GARV, which allow the improvement and even the optimization of the working process.

The degree of crushing is influenced by the speed of movement. Certainly, the parameters have a great influence on the degree of crushing: the rotor speed and the number of knives on the rotor. Not enough experiments could be performed to estimate these dependencies.

The fuel consumption and the fuel consumption specific to the productivity unit also depend on the working speed, they can even present optimal points of the working speed (working speeds at which minimum consumptions take place). Fuel consumption also depends on the rotor speed and the number of knives mounted on each rotor. Because of the few experiments, not enough data were available to study these addictions.

The tensile strength in the experimental interval has a minimum point depending on the working speed and this must be confirmed by new experiments. The same is valid for consumption, closely related to soil tillage draft force. The soil tillage draft force of the GARV also increases with the number of knives mounted on the rotor, which also increases the degree of crushing. These dependencies show that it is possible to work at slightly higher working speeds if the rotor speed and, possibly, the number of knives is increased.

Therefore, there are further directions of study. More precisely, an extensive experimental program that includes several at least a few tens or over a hundred experiments in which to vary the working speed, the rotor speed and the number of working parts on the rotor. Such experiments will validate the present conclusions or correct them, but, first, they will be able to provide other important relations in the dynamics of the tractor-GARV system.

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