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Student-doctorand
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RESEARCH ON OPTIMIZING THE POWER BALANCE OF A PLOWING AGGREGATE COMPRISED OF A 180 HP TRACTOR AND A 5-MOLDBOARD PLOW

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CERCETĂRI PRIVIND OPTIMIZAREA BILANȚULUI DE PUTERE AL UNUI AGREGAT DE ARAT FORMAT DINTR-UN TRACTOR DE 180 CP ȘI UN PLUG CU 5 TRUPIȚE

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ABSTRACT

Plowing is recognized as an essential agricultural task that cannot yet easily be substituted with alternative soil processing methods due to its significance. However, it is also one of the most fuel-intensive operations. The main objective of this paper is to determine the optimal operational parameters (working speed and working width) of a plowing aggregate composed of a 180 HP tractor and a 5-moldboard plow, which ensures the full utilization of the tractor engine's power and the use of the aggregate at its maximum working capacity, respectively, achieving an optimal power balance.

REZUMAT

Lucrarea de arat este recunoscută ca fiind una încă greu de înlocuit de alte lucrări de pregătire a patului germinativ datorită importanței și utilității acesteia. În același timp, lucrarea de arat este una dintre cele mai mari consumatoare de combustibil din întreg ciclul de cultivație. Obiectivul principal al lucrării constă în determinarea parametrilor de operare optimi pentru un agregat de arat compus dintr-un tractor de 180 CP și un plug cu 5 trupițe, care să asigure utilizarea în întregime a puterii motorului tractorului și folosirea agregatului la capacitatea maximă de lucru, respectiv, realizarea un bilanț de putere optimal.

INTRODUCTION

Plowing is a crucial agricultural operation that demands significant fuel consumption. To reduce the significant amount of fuel required for seedbed preparation operations, particularly for plowing, the tractor-implement aggregates must be properly configured, and the operating parameters must be selected to ensure the full utilization of the tractor engine's power *(Șandru et al., 1983; Croitoru et al., 2017)*. Additionally, the soil processing equipment should operate at its maximum working capacity while maintaining an optimal power balance *(Hunt, 1986)*.

Studies on soil-machine interaction aim to provide scientific insights into the dynamics between tillage tools, traction devices, and the terrain they operate on. Key variables examined include the forces needed to operate tillage tools, vertical and lateral forces acting on them, patterns of soil failure, displacement of soil particles, forces at the wheel-soil interface, wheel sinkage, rolling resistance, contact area of wheels, and soil stress at various depths *(Ani et al., 2018; Gheres et al., 2013)*.

The resistance force to the movement of agricultural aggregates arises from the friction between the wheels and the soil surface, the friction of the axles in the wheel bearings, and the deformation of the soil by the aggregate's wheels *(Dobrescu, 1981)*. This force is influenced by the type and construction of the driving and supporting wheels, the weight of the aggregate, and the properties of the soil on which it operates. On loose, highly moist, or uneven soils, the resistance to movement is higher compared to operating on compacted, smooth-surfaced soils. Soil surface irregularities increase rolling resistance due to additional soil deformation, deviation of the machines in the aggregate from the forward direction, and the emergence of additional inertial forces *(Gill, Vanden Berg, 1968; Kheiralla et al., 2004)*.

Rolling resistance is also affected by the relaxation time of the soil and the tires after their mutual deformation at the point of contact. As relaxation time increases, soil deformation decreases, and vice versa *(Koolen et al., 1983)*. Low-pressure tires, typical for agricultural machines, have a larger contact area with the soil, resulting in lower specific pressure and reduced soil deformation. Consequently, rolling resistance on

deformable soil surfaces is lower, but the tires undergo more significant deformations, reducing their service life. On loose soils, aggregates equipped with low-pressure tires or tracks exhibit lower resistance to movement compared to those with metal wheels or high-pressure tires *(Bennett et al., 2019; Jun et al., 2024)*.

The traction resistance of agricultural machines, like other aggregate parameters, exhibits a pronounced random nature *(Gheres et al., 2013)*. Several factors influence the variability characteristics, the most important being soil type, soil compaction, moisture, non-uniformity, texture, and structure of the processed soil, as well as certain variations occurring at the drive wheels and articulation points of the aggregate. These factors have a more pronounced effect on aggregates with high-powered tractors and at high working speeds *(Abo et al., 2011; Biris et al., 2017)*.

The variation in the working resistance of agricultural machines also leads to the tractor engine operating under unstable conditions. Depending on this variation and the engine load coefficient, power losses of up to 10-15% can occur. The load regime of the aggregate machines induces random dynamic processes in all aggregate components *(Dobrescu, 1981; Md-Tahir et al., 2021)*.

The random nature of the engine torque further affects the tractor's traction characteristics. A negative impact can be observed on the adhesion force and the slippage of the driving wheels. At equal traction forces, higher dispersion in their value leads to increased tractor slippage. Additionally, when the frequency of traction resistance variation is high, significant power losses occur due to slippage *(Md-Tahir et al., 2021; McKyes, 1985)*. The traction resistance value of agricultural machines considered in calculations is the average value obtained from statistical processing of traction diagrams recorded during operation *(Trendafilov et al., 2023; Varani et al., 2023)*. As the working speed increases, the working resistance of agricultural machines also increases. The rate of this increase depends on the type of working parts of the machine and the nature of the working process *(Cardei et al., 2023)*.

It is imperative to determine the optimal operating parameters for agricultural implements designed for seedbed preparation, ensuring full utilization of the tractor engine's power and operating the implement at maximum working capacity, thereby achieving an optimal power balance *(Legay, 1988; Vlăduț et al., 2018)*. Currently, this can be accomplished using analytical and numerical calculation algorithms, which can be implemented on modern agricultural tractors and are presented within this study *(Vlăduțoiu et al., 2017; Simionescu et al., 1995)*.

The main objective of the paper is to determine the optimal operational parameters of a plowing aggregate composed of a 180 HP tractor and a 5-moldboard plow, specifically: v - working speed and B - working width, which ensure the full utilization of the tractor engine's power and the use of the aggregate at its maximum working capacity. As will be further shown, the power balance equation can be used as an objective function for optimizing the power balance.

MATERIALS AND METHODS

The study presented in this paper was conducted for an aggregate consisting of a 180 HP tractor (A 1800-A) and a variable working width plough with 5 moldboards (PP5VM), designed to perform plowing operations on flat terrain or slopes with a maximum inclination of 6° (figure 1).



Fig. 1 - The 180 HP tractor and a plough with variable working width with 5 moldboards

The aggregate requires power for movement and power for performing the plowing operation. The tractor's drive wheels generate the power necessary to operate the aggregate. As a constraint, the coefficient of utilization of travel time, τ_d, can be considered, knowing that its level is proportional to the working capacity of the aggregate *(Dobrescu, 1981)*.

The power balance of a plowing aggregate can be expressed by the following equation:

$$P_M \cdot \tau_M = \frac{f_1 \cdot G \cdot v + f_v \cdot G \cdot v^2 + k \cdot a \cdot B \cdot v + \varepsilon \cdot a \cdot B \cdot v^3}{\eta_T \cdot (1-\delta_p)} \quad (1)$$

where: P_M - is the power developed by the engine, (W); η_M - the engine power utilization coefficient, η_p - the efficiency of the transmission at the power take-off and the driving wheels; f_1 - proportionality coefficient; f_v - coefficient of resistance increase due to speed growth, (s/m); δ_p - tractor slippage; G - the weight of the aggregate, (N); v – the working speed (m/s); B – the working width, (m); a – the working depth, (m); k – the resistance to deformation and crumbling of the soil furrow, (N/m²); ε - the coefficient characterizing the shape of the crown and the properties of the soil, (N·s²/m⁴).

The terms in the first fraction of equation (1) represent the power required for moving the aggregate, while the terms in the second fraction represent the power required for plowing. If the coefficient k is determined without considering the friction between the working parts and the furrow, then the last two terms correspond to Goriacichin's formula *(Cardei et al., 2023)*. These frictions are accounted for when determining the coefficients f_1 and f_v.

If it is considered that there is a relationship between the weight of the aggregate and the working width in the form of $G_B = \alpha \cdot B$, where α is the specific weight of the aggregate per working width, (N/m), the objective function becomes:

$$P_M \cdot \eta_M \cdot \eta_T \cdot (1-\delta_p) = f_1 \cdot \alpha \cdot B \cdot v + f_v \cdot \alpha \cdot B \cdot v^2 + k \cdot a \cdot B \cdot v + \varepsilon \cdot a \cdot B \cdot v^3 \quad (2)$$

The optimal parameters B and v are those that ensure maximum productivity at the engine power level. Since the technical productivity of plowing aggregates is related to the level of the time utilization coefficient of travel, τ_d, this constitutes the constraint:

$$\frac{v_g \cdot L}{v_g \cdot L + v \cdot (\Omega + m_1 \cdot B)} - \tau_d = 0 \quad (3)$$

The optimal solution can be found using the Lagrange multiplier and the constraint *(Simionescu et al., 1995)*:

$$\begin{cases} \frac{\partial P_M}{\partial v} + \lambda \cdot \frac{\partial \tau_d}{\partial v} = 0 \\ \frac{\partial P_M}{\partial B} + \lambda \cdot \frac{\partial \tau_d}{\partial B} = 0 \end{cases} \quad (4)$$

and the constraint:

$$\frac{m}{m + v \cdot (\Omega + m_1 \cdot B)} - \tau_d = 0 \quad (5)$$

in which m and m_1 are operating parameters dependent on the idle travel speed of the aggregate (v_g), the plot length (L), the length of the path travelled without working (S_g), the plot width (C), ($m = v_g \cdot L$, $m_1 = S_g^3 / C$).

The terms in the system of equations (4) are determined using *(Dobrescu, 1981)*:

$$\frac{\partial P_M}{\partial v} = f_1 \cdot \alpha \cdot B + 2 \cdot f_v \cdot \alpha \cdot B \cdot v + k \cdot a \cdot B + 3 \cdot \varepsilon \cdot a \cdot B \cdot v^2 \quad (6)$$

$$\frac{\partial P_M}{\partial B} = f_1 \cdot \alpha \cdot v + f_v \cdot \alpha \cdot v^2 + k \cdot a \cdot v + \varepsilon \cdot a \cdot v^3 \quad (7)$$

$$\frac{\partial \tau_d}{\partial v} = \frac{m \cdot (\Omega + m_1 \cdot B)}{[m + v \cdot (\Omega + m_1 \cdot B)]^2} \quad (8)$$

$$\frac{\partial \tau_d}{\partial B} = \frac{m_1 \cdot m \cdot v}{[m + v \cdot (\Omega + m_1 \cdot B)]^2} \quad (9)$$

A system of three equations with three unknowns is obtained:

$$\begin{cases} f_1 \cdot \alpha \cdot B + 2 \cdot f_v \cdot \alpha \cdot B \cdot v + k \cdot a \cdot B + 3 \cdot \varepsilon \cdot a \cdot B \cdot v^2 - \lambda \cdot \frac{m \cdot (\Omega + m_1 \cdot B)}{[m + v \cdot (\Omega + m_1 \cdot B)]^2} = 0 \\ f_1 \cdot \alpha \cdot v + f_v \cdot \alpha \cdot v^2 + k \cdot a \cdot v + \varepsilon \cdot a \cdot v^3 - \lambda \cdot \frac{m_1 \cdot m \cdot v}{[m + v \cdot (\Omega + m_1 \cdot B)]^2} = 0 \\ \frac{m}{m + v \cdot (\Omega + m_1 \cdot B)} - \tau_d = 0 \end{cases} \quad (10)$$

The variable λ is eliminated by equating its value from the first equation of the system (10) with the value obtained from the second equation, resulting in:

$$3 \cdot v^2 + 2 \cdot v \cdot \left[\frac{m \cdot (1-\tau_d)}{\tau_d \cdot \Omega} - \frac{\alpha \cdot f_v}{\varepsilon \cdot a} \right] + \frac{f_1 \cdot (f_v \cdot \alpha + k \cdot a \cdot \Omega}{\varepsilon \cdot a \cdot \Omega} = 0 \quad (11)$$

from which the expression for the optimal speed is obtained:

$$v_{opt} = \frac{1}{3} \cdot \left[\frac{m \cdot (1-\tau_d)}{\tau_d \cdot \Omega} - \frac{\alpha \cdot f_v}{\varepsilon \cdot a} + \sqrt{\left(\frac{\alpha \cdot f_v}{\varepsilon \cdot a} \right)^2 + \left(\frac{m \cdot (1-\tau_d)}{\tau_d \cdot \Omega} \right)^2 + \frac{\alpha \cdot f_v \cdot m \cdot (1-\tau_d)}{\varepsilon \cdot a \cdot \tau_d \cdot \Omega} - \frac{3 \cdot (\alpha \cdot f_1 + k \cdot a)}{\varepsilon \cdot a}} \right] \quad (12)$$

From the third equation of the system (10), it results:

$$B_{opt} = \frac{m \cdot (1-\tau_d) - \tau_d \cdot \Omega \cdot v_{opt}}{\tau_d \cdot m_1 \cdot v_{opt}} \quad (13)$$

The productivity of the aggregate is:

$$U_{\tau_d} = v_{opt} \cdot B_{opt} \cdot \tau_d \quad (14)$$

The power required to operate the aggregate is calculated using the following equation:

$$P_{min} = f_1 \cdot \alpha \cdot B_{opt} \cdot v_{opt} + f_v \cdot v^2 \cdot \alpha \cdot B_{opt} + B_{opt} \cdot v_{opt} \cdot a \cdot k + \varepsilon \cdot a \cdot B_{opt} \cdot v_{opt}^3 \quad (15)$$

The above calculation can be applied when studying the parameters of a new implement or when forecasting the development of plowing aggregates.

For existing aggregates, the relationship between the weight of the aggregate and its components is established using the following formula:

$$G = G_0 + G_B = G_0 + \alpha \cdot B \quad (16)$$

where: G_0 - represents the constant weight of the aggregate (the weight of the tractor and the carrying device), and α - is the specific weight of the part that changes with the working width B.

In this case, the mathematical model takes the form of:

$$P_M \cdot \eta_M \cdot \eta_T \cdot (1-\delta) = f_1 \cdot G_0 \cdot v + f_1 \cdot \alpha \cdot B \cdot v + f_v \cdot G_0 \cdot v^2 + f_v \cdot \alpha \cdot B \cdot v^2 + k \cdot a \cdot B \cdot v + \varepsilon \cdot a \cdot B \cdot v^3 \quad (17)$$

and:

$$\frac{m}{m + v \cdot (\Omega + m_1 \cdot B)} - \tau_d = 0 \quad (18)$$

By deriving the objective function and the constraints, the following is obtained:

$$\begin{cases} \frac{\partial P_M}{\partial v} = f_1 \cdot (G_0 + \alpha \cdot B) + 2 \cdot f_v \cdot v \cdot (G_0 + \alpha \cdot B) + k \cdot a \cdot B + 3 \cdot \varepsilon \cdot a \cdot B \cdot v^2 \\ \frac{\partial P_M}{\partial B} = f_1 \cdot \alpha \cdot v + f_v \cdot \alpha \cdot v^2 + k \cdot a \cdot v + \varepsilon \cdot a \cdot v^3 \\ \frac{\partial \tau_d}{\partial v} = \frac{m \cdot (\Omega + m_1 \cdot B)}{[m + v \cdot (\Omega + m_1 \cdot B)]^2} \\ \frac{\partial \tau_d}{\partial B} = \frac{m_1 \cdot m \cdot v}{[m + v \cdot (\Omega + m_1 \cdot B)]^2} \end{cases} \quad (19)$$

A system of three equations with three unknowns is formulated using the coefficient λ:

$$\begin{cases} f_1 \cdot G + f_1 \cdot \alpha \cdot B + 2 \cdot f_v \cdot v \cdot G + 2 \cdot f_v \cdot \alpha \cdot B \cdot v + k \cdot a \cdot B + 3 \cdot a \cdot B \cdot v^2 - \lambda \cdot \frac{m \cdot (\Omega + m_1 \cdot B)}{[m + v \cdot (\Omega + m_1 \cdot B)]^2} = 0 \\ f_1 \cdot \alpha \cdot v + f_v \cdot \alpha \cdot v^2 + k \cdot a \cdot v + \varepsilon \cdot a \cdot v^3 - \lambda \cdot \frac{[m + v \cdot (\Omega + m_1 \cdot B)]^2}{m_1 \cdot m \cdot v} = 0 \\ \frac{m}{m + v \cdot (\Omega + m_1 \cdot B)} - \tau_d = 0 \end{cases} \quad (20)$$

By eliminating the variable λ and performing the simplifications, the following is obtained:

$$f_1 \cdot \alpha \cdot \Omega + f_v \cdot \alpha \cdot v \cdot \Omega + k \cdot a \cdot \Omega v^2 - f_1 \cdot G \cdot m_1 - 2 \cdot f_v \cdot v \cdot \Omega B \cdot m_1 - 2 \cdot \varepsilon \cdot a \cdot B \cdot v^2 \cdot m_1 = 0 \quad (21)$$

If B is replaced in the last equation of the system (20), the result is:

$$3 \cdot v^2 + 2 \cdot v \cdot \left[\frac{f_v \cdot (\alpha \cdot \Omega - G \cdot m_1)}{\varepsilon \cdot a \cdot \Omega} - \frac{m \cdot (1-\tau_d)}{\tau_d \cdot \Omega} \right] + \frac{f_1 \cdot (\alpha \cdot \Omega - G \cdot m_1 + k \cdot a \cdot \Omega)}{\varepsilon \cdot a \cdot \Omega} - \frac{f_v \cdot \alpha \cdot m_1 \cdot (1-\tau_d)}{\varepsilon \cdot a \cdot \tau_d \cdot \Omega} = 0 \quad (22)$$

from which the expression for the optimal speed results:

$$v_{opt} = \frac{1}{3} \cdot \left[\frac{m \cdot (1-\tau_d)}{\tau_d \cdot \Omega} - \frac{f_v \cdot (\alpha \cdot \Omega - m_1 \cdot G)}{\varepsilon \cdot a \cdot \Omega} + \sqrt{\left(\frac{m \cdot (1-\tau_d)}{\tau_d \cdot \Omega} \right)^2 + \frac{f_v \cdot m \cdot (1-\tau_d) \cdot (\alpha \cdot \Omega + 2 \cdot m_1 \cdot G)}{\varepsilon \cdot a \cdot \tau_d \cdot \Omega^2} \left(\frac{\alpha \cdot f_v}{\varepsilon \cdot a} \right)^2 - \frac{3 \cdot f_1 \cdot (\alpha \cdot \Omega - m_1 \cdot G) + 3 \cdot k \cdot a \cdot \Omega)}{\varepsilon \cdot a \cdot \Omega}} \right] \quad (23)$$

The optimal working width, B_{opt}, is determined by the relationship of the maximum working capacity of the aggregate:

$$B_{opt} = \frac{m \cdot (1-\tau_d) - \tau_d \cdot \Omega \cdot v_{opt}}{\tau_d \cdot m_1 \cdot v_{opt}} \quad \text{(m)} \quad (24)$$

If the maximum loading of the tractor is desired, the following relation (25) results:

$$B_{opt} = \frac{P_a - f_1 \cdot G_0 \cdot v_{opt} - f_v \cdot G_0 \cdot v_{opt}^2}{f_1 \cdot a \cdot v_{opt} + f_v \cdot a \cdot v_{opt}^2 + k \cdot a \cdot v_{opt} + \varepsilon \cdot a \cdot v_{opt}^3} \text{ (m)} \quad (25)$$

If in equation (23) of the working speed, $G_B = \alpha \cdot B = 0$ is assumed, equation (12) is obtained. If it is assumed that the weight of the entire aggregate is constant, i.e., $\alpha = 0$, the following results:

$$v_{opt} = \frac{1}{3} \cdot \left[\frac{m \cdot (1 - \tau_d)}{\tau_d \cdot \Omega} + \frac{f_v \cdot m_1 \cdot G}{\varepsilon \cdot a \cdot \Omega} + \sqrt{\left(\frac{m_1 \cdot G \cdot f_v}{\varepsilon \cdot a \cdot \Omega} \right)^2 + \left(\frac{m \cdot (1 - \tau_d)}{\tau_d \cdot \Omega} \right)^2 + \frac{2 \cdot m_1 \cdot G \cdot f_v \cdot m \cdot (1 - \tau_d)}{\varepsilon \cdot a \cdot \tau_d \cdot \Omega^2} + \frac{3 \cdot f_v \cdot m_1 \cdot G - 3 \cdot k \cdot a \cdot \Omega}{\varepsilon \cdot a \cdot \Omega}} \right] \quad (26)$$

By applying equation (25) and the corresponding computational algorithm, a Python code was developed, allowing the calculation and plotting of the optimal values for the plow's total working width (figure 2.a), as well as the 3D generation of this dependency on the working speed and the utilization coefficient of the displacement time (τ_d) (figure 2.b).

```
import numpy as np
import matplotlib.pyplot as plt

m_1 = 45
m = 700
omega = 40

tau_d_values = [0.7, 0.71, 0.72, 0.73, 0.74, 0.75, 0.76, 0.77, 0.78]

v_opt = np.linspace(0.5, 2.5, 100)

plt.figure(figsize=(8, 6))

for tau_d in tau_d_values:
    B_opt = (m * (1 - tau_d) + tau_d * omega * v_opt) / (tau_d * m_1 * v_opt)
    # Filtrare pentru valorile B_opt în intervalul [0.8, 2]
    mask = (B_opt >= 0.8) & (B_opt <= 2)
    plt.plot(v_opt[mask], B_opt[mask], label=f"$\\tau_d = {tau_d}$")

plt.title("Graph of $B_{opt}$ vs $v_{opt}$ for Different $\\tau_d$")
plt.xlabel("$v_{opt}$ (m/s)")
plt.ylabel("$B_{opt}$ (m)")
plt.ylim(0.8, 2)
plt.axhline(0, color='black', linewidth=0.8, linestyle='--')
plt.legend()
plt.grid()

plt.show()
```

a)

b)

Fig. 2 – Python code for determining the optimal working width of a plow with 5 bodies

```
import numpy as np
import matplotlib.pyplot as plt

G_pl = 30000  # N
f_pl = 0.35
k_0 = 50000  # N/m^2
eps = 1000  # N/m^3
B = 1.5

a_values = np.linspace(0.05, 0.3, 100)

v_pl_values_fixed = [1, 1.5, 2, 2.5]

plt.figure(figsize=(8, 6))

for v in v_pl_values_fixed:
    R_pl_values = G_pl * f_pl + k_0 * a_values * B + eps * a_values * B * (v ** 2)
    plt.plot(a_values, R_pl_values, label=f"v_pl = {v} m/s")

plt.title("Graph of $R_{pl}$ vs $a$ for Different Values of $v_{pl}$")
plt.xlabel("$a$ (m)")
plt.ylabel("$R_{pl}$ (N)")
plt.grid(True)
plt.legend()

plt.tight_layout()
plt.show()
```

a)

```
import numpy as np
import matplotlib.pyplot as plt

G_pl = 30000  # N
f_pl = 0.35
k_0 = 50000  # N/m^2
eps = 1000  # N/m^3

B_values = [1.25, 1.35, 1.45, 1.55, 1.65]

a_values = np.linspace(0.05, 0.3, 100)

v_pl = 2

plt.figure(figsize=(8, 6))

for B in B_values:
    R_pl_values = G_pl * f_pl + k_0 * a_values * B + eps * a_values * B * (v_pl ** 2)
    plt.plot(a_values, R_pl_values, label=f"B = {B} m")

plt.title("Graph of $R_{pl}$ vs $a$ for Different Values of $B$")
plt.xlabel("$a$ (m)")
plt.ylabel("$R_{pl}$ (N)")
plt.grid(True)
plt.legend()

plt.tight_layout()
plt.show()
```

b)

Fig. 3 – Python code for determining the traction force of a plow with 5 plowshares

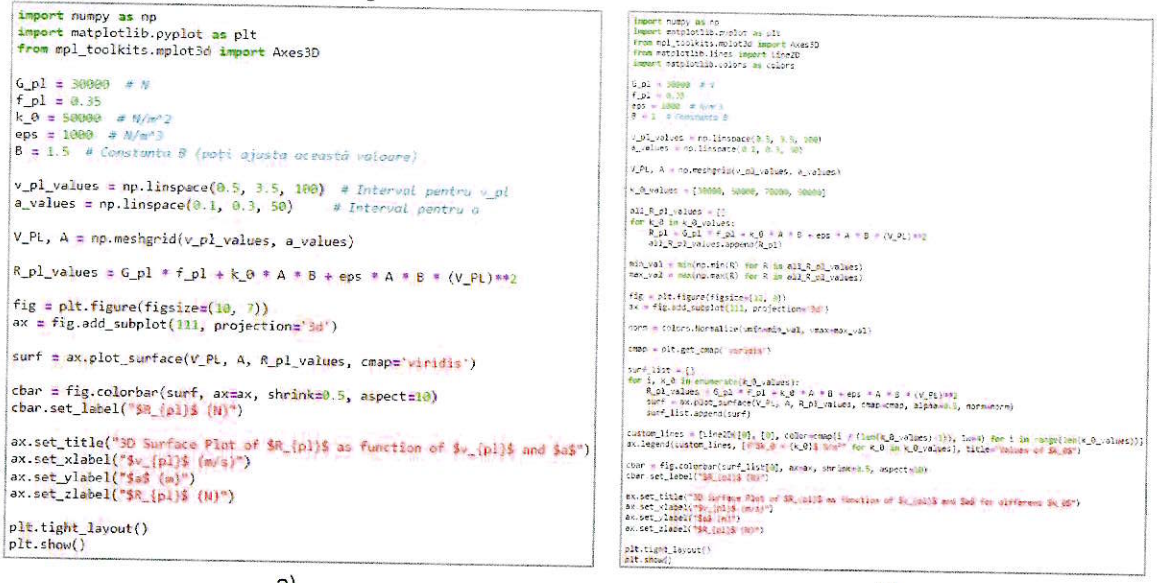
For the plowing work, the traction resistance force of the plow can be estimated using the following relation:

$$R_p = k_0 \cdot a \cdot B_l \quad \text{[N]} \quad (27)$$

in which: k_0 represents the specific soil resistance to plowing, $(2 - 10) \cdot 10^4$ [N/m²]; a is the working depth [m]; B_l is the total working width of the plow [m].

In figure 3.a, a Python code is presented that allows the calculation and graphical plotting of the dependency of the plow's draft resistance on the working depth for different working speeds, and in figure 3.b, the same dependency is shown, but for various total working widths of a plow with 5 plowshares and a variable working width.

In figure 4.a, a Python code is presented that allows the calculation and 3D plotting of the plow's traction resistance as a function of working depth and working speed for a single soil type, while in figure 4.b, the same dependence is shown for four soil types with different specific resistances to tillage in the case of a plow with 5 plowshares and a variable working width.



```python
import numpy as np
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D

G_pl = 30000  # N
f_pl = 0.35
k_0 = 50000  # N/m^2
eps = 1000  # N/m^3
B = 1.5  # Constanta B (poti ajusta aceasta valoare)

v_pl_values = np.linspace(0.5, 3.5, 100)  # Interval pentru v_pl
a_values = np.linspace(0.1, 0.3, 50)      # Interval pentru a

V_PL, A = np.meshgrid(v_pl_values, a_values)

R_pl_values = G_pl * f_pl + k_0 * A * B + eps * A * B * (V_PL)**2

fig = plt.figure(figsize=(10, 7))
ax = fig.add_subplot(111, projection='3d')

surf = ax.plot_surface(V_PL, A, R_pl_values, cmap='viridis')

cbar = fig.colorbar(surf, ax=ax, shrink=0.5, aspect=10)
cbar.set_label("$R_{pl}$ (N)")

ax.set_title("3D Surface Plot of $R_{pl}$ as function of $v_{pl}$ and $a$")
ax.set_xlabel("$v_{pl}$ (m/s)")
ax.set_ylabel("$a$ (m)")
ax.set_zlabel("$R_{pl}$ (N)")

plt.tight_layout()
plt.show()
```

a) b)

Fig. 4 – Python code for determining the 3D variation of the draft force of a plow with 5 plowshares

The power required to pull the plow during the plowing process is calculated:

$$P_t = k_0 \cdot a \cdot B_l \cdot v_l \quad [\text{W}] \tag{28}$$

where v_l represents the working speed of the tillage aggregate [m/s].

The energy consumption per unit of processed surface is calculated using the following relation:

$$E_{ha} = \frac{P_t}{S_h} \quad [\text{Wh/ha}] \tag{29}$$

where S_h represents the working capacity of the plowing aggregate [ha/h].

In figure 5.a, a Python code is presented which, based on relation (29), allows for the calculation and graphical plotting of the dependence of energy consumption per unit of worked surface for a plow with 5 moldboards with variable working width, for different working depths according to the specific resistance to plowing, and in figure 5.b, the same dependence is calculated and plotted in 3D.

```python
import numpy as np
import matplotlib.pyplot as plt

B_l = 1.5
v_l = 2
W_h = 0.25

k_0_values = np.linspace(2e4, 10e4, 500)

a_values = [0.15, 0.175, 0.2, 0.215, 0.25, 0.275, 0.3]

plt.figure(figsize=(8, 6))

for a in a_values:
    P_t = k_0_values * a * B_l * v_l
    E_ha = P_t / W_h
    plt.plot(k_0_values, E_ha, label=f"a = {a}")

plt.title("Graph of $E_{ha}$ vs $k_0$ for Different $a$ values")
plt.xlabel("$k_0$ [N/m²]")
plt.ylabel("$E_{ha}$ [Wh/ha]")
plt.legend()

plt.grid(True)
plt.show()
```

a)

```python
import numpy as np
import matplotlib.pyplot as plt
from mpl_toolkits.mplot3d import Axes3D

B_l = 1.5
v_l = 2
W_h = 0.25

k_0_values = np.linspace(2e4, 10e4, 500)
a_values = np.linspace(0.15, 0.3, 6)

K0, A = np.meshgrid(k_0_values, a_values)

E_ha = (K0 * A * B_l * v_l) / W_h

fig = plt.figure(figsize=(10, 8))
ax = fig.add_subplot(111, projection='3d')

surf = ax.plot_surface(K0, A, E_ha, cmap='viridis')

ax.set_title("Graph of $E_{ha}$ vs $k_0$ and $a$")
ax.set_xlabel("$k_0$ [N/m²]")
ax.set_ylabel("$a$ [m]")
ax.set_zlabel("$E_{ha}$ [Wh/ha]")

cbar = fig.colorbar(surf, ax=ax, shrink=0.5, aspect=5)
cbar.set_label("$E_{ha}$ [Wh/ha]")

plt.show()
```

b)

Fig. 5 – Python code for determining the variation in energy consumption per unit area worked for a plow with 5 moldboards

RESULTS

Through classical analytical calculation, applying the mathematical models embodied in equations (25) and (26), for a plowing unit operating under the conditions given in the first column of Table 1, the optimal parameters are obtained, which are found in the second column of the same table.

Table 1

The parameters resulting from the calculation for a plowing aggregate composed of a tractor A-1800 A and the PSP-5 (35) plow

The conditions of the plowing aggregate formed by the A-1800 A tractor and the PSP-5 (35) plow.	The parameters of the plowing aggregate resulting from the calculation
The weight of the tractor: G_t=97000 N *The weight of the plow:* G_p=30000 N *The weight of the aggregate:* $G=G_t+G_p$=127000 N τ_d=0.9; Ω=40; m_1=10; k=35000 N/m²; f_1=0.1; f_i=0.09; L=1000 m; v_g=0.5 m/s; a=0.25 m; ε =3000 N·s²/m⁴	v_{opt}=2.03 m/s B_{opt}=1.5 m

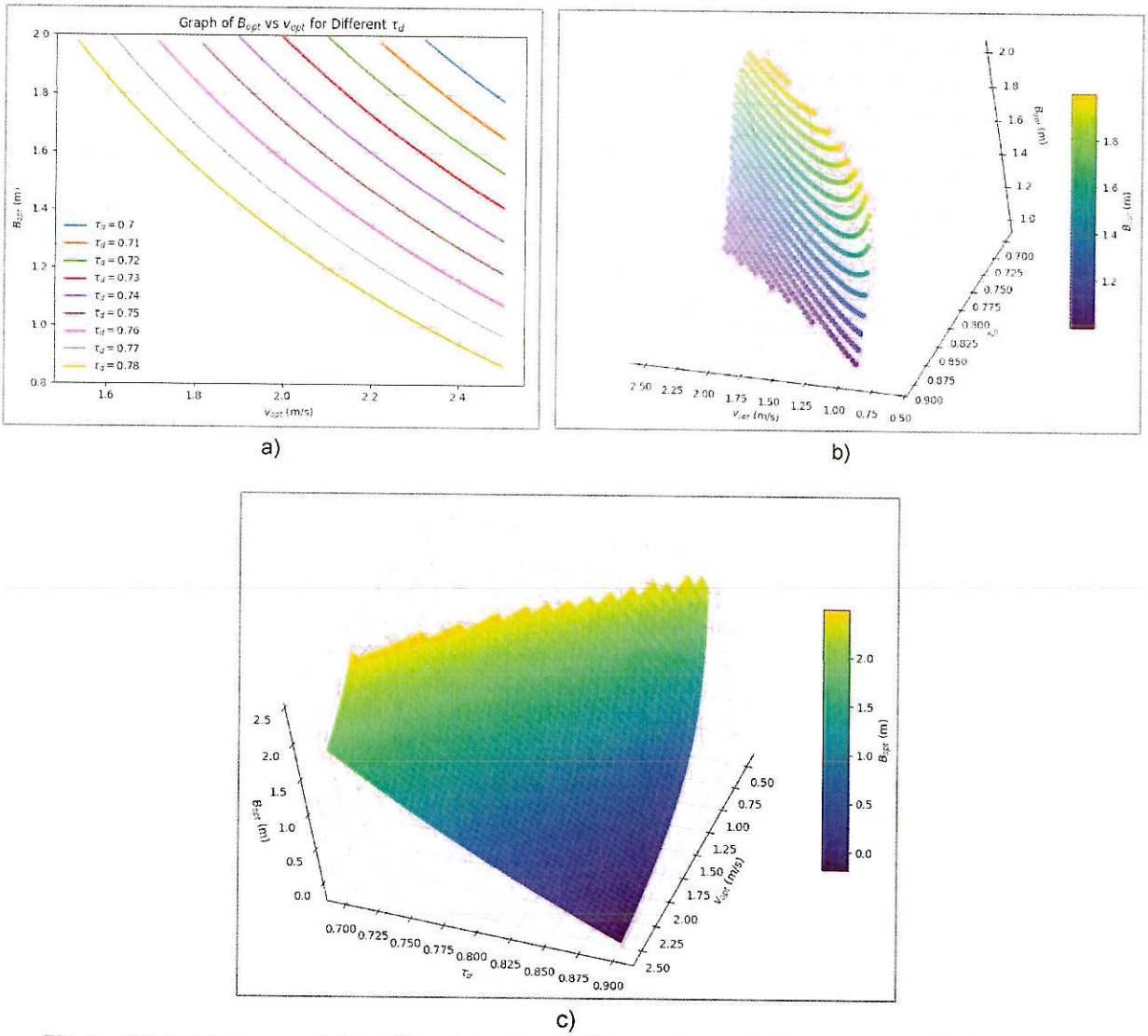
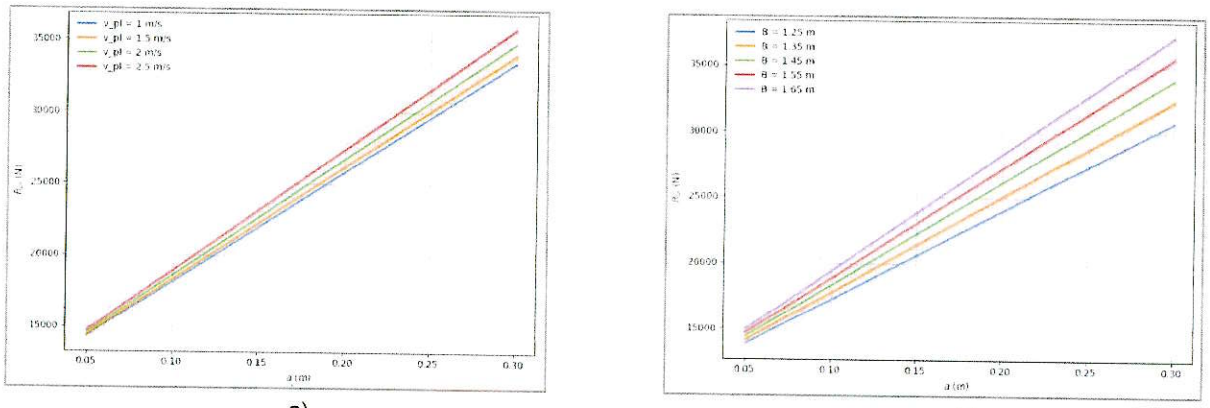


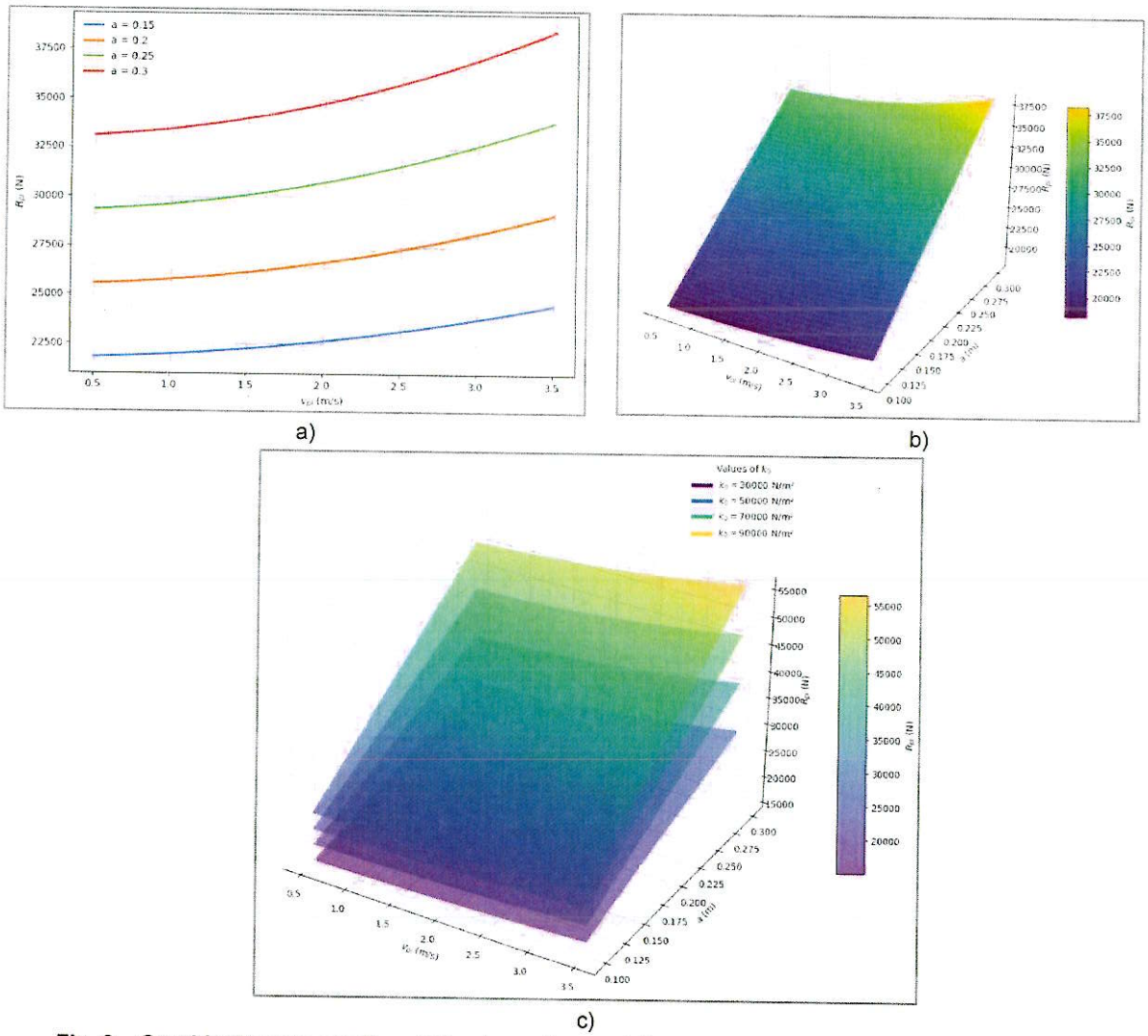
Fig. 6 – Graphical representation of the dependency of the optimal plowing width on the working speed and the travel time utilization coefficient for a plow with 5 moldboards

Using the calculation algorithms and Python codes presented in figure 2, the optimal values for the plow's total working width were calculated and plotted (figure 6.a), as well as the 3D variant of this dependency on working speed and the travel time utilization coefficient (τ_d) (figure 6.b). In addition, figure 6.c shows the 3D graph of the dependency of the optimal working width on the working speed - with values in the range of 0.5 - 2.5 m/s - and on the travel time utilization coefficient - with values in the range of 0.7–0.9.



a) b)

Fig. 7 – Graphical representation of the dependence of the draft force of a plow with 5 moldboards at working depth for different working speeds and different total working widths



a) b)

c)

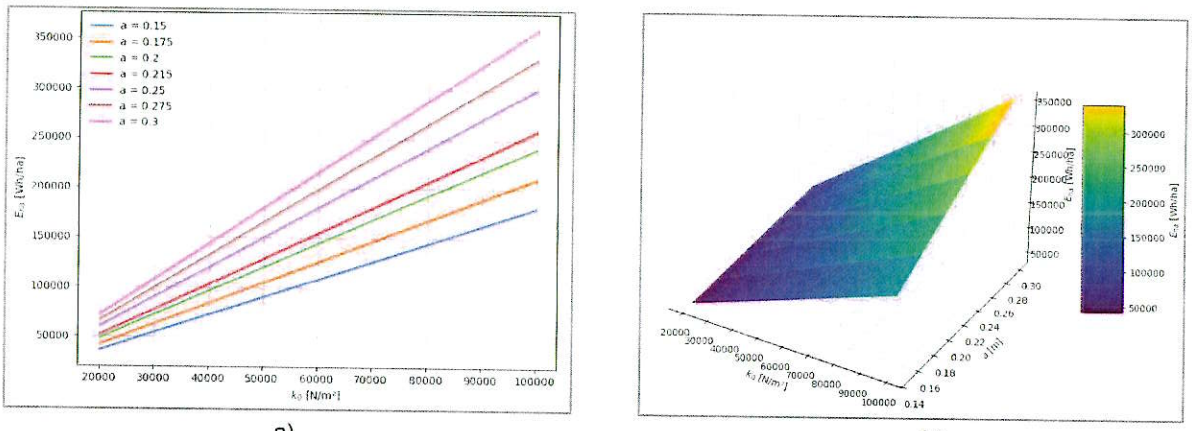
Fig. 8 – Graphical representation of the dependency of the traction force of a plow with 5 plowshares on working speed for various working depths and operating speeds

Using the calculation algorithms and Python codes presented in figure 3.a and figure 3.b, the dependence of the plow's draft resistance on working depth was calculated and plotted for different working speeds (figure 7.a), as well as the same dependence for various total working widths of a 5-furrow plow with variable working width (figure 7.b). It is easy to observe that the plow's draft resistance increases with the increase in working depth, for the different working speeds and various total working widths.

The draft force of the plow as its traveling speed increases, with the dependency $R_{pl}=f(v_{pl})$ being nonlinear (figure 8.a). The increase in draft force is smaller at lower speeds (0.5–2 m/s) and much more significant at higher working speeds (2–3.5 m/s).

In figure 8.b, the 3D graphical representation of the plows's draft force is shown, with working depth and working speed as the independent parameters, for a single type of soil. This was generated using the calculation algorithm and the Python program presented in figure 4.a. In figure 8.c, the same dependency is displayed, but for four different types of soil, using the calculation algorithm and Python code presented in figure 4.b.

Using the computational algorithms and the Python code presented in figure 5.a, the dependence based on relation (29) of the energy consumption per unit worked area for a plow with 5 moldboards of variable working width has been calculated and plotted, for different working depths as a function of the specific tillage resistance (different soil types) (figure 9.a). In figure 9.b, the 3D dependence of the energy consumption per unit worked area is presented as a function of the independent variables: working depth and specific tillage resistance, calculated and generated using the Python code presented in figure 5.b. The energy consumption per unit worked area for a plow with 5 moldboards of variable working width increases with an increasing working depth. The soil category and its physico-mechanical properties (specific tillage resistance) have a significant influence on the mechanical energy consumption.



a) b)

Fig. 9 – Graphical representation of the dependency of the traction force of a plow with 5 plowshares on working speed for different working depths and operating speeds

CONCLUSIONS

Optimal operation of the implements used for plowing is essential for efficient resource use and cost reduction. Fully utilizing the tractor's engine power and operating the plowing implement at its maximum capacity enables an optimal power balance. The optimal operating regime can be determined through numerical algorithms based on Lagrange multipliers, using computing programs (Python code in this case). To achieve maximum productivity at the engine power level, it is necessary to calculate the optimal working speed and optimal working width, depending on the coefficient of utilization of the plowing implement's transit time.

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RESEARCH ON DETERMINING THE PERFORMANCE OF A VARIABLE WIDTH PLOUG DESIGNED FOR HIGH-POWER TRACTORS (180-240 HP)

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Abstract

It is known that plowing remains a task difficult to replace with other alternative soil processing works, due to its importance. At the same time, plowing remains work that involves the highest fuel consumption. On the other hand, it is known that the physical and mechanical characteristics of the processed soil can vary greatly from one plot to another, and the plow intended for plowing work must be properly adjusted so that the tractor operating in aggregate works under optimal conditions. Variable plowing width prove to be the most suitable for adapting to soil conditions and tractor traction performance. For large agricultural operations, the use of high-power tractors is recommended to ensure that work is carried out with a minimum number of passes. In this paper, the results obtained from experimental trials conducted in Romania using a variable width plow equipped with five moldboards and powered by a 200 HP tractor are presented. The trials have been conducted for different working widths/moldboards (30, 35, 40, 45 cm), different working depths (20, 25, 30 cm), and different working speeds, which allowed, on one hand, the determination of qualitative work indices, and on the other hand, obtaining the energy indices of the tractor-plough unit (fuel consumption, working capacity, slippage, specific fuel consumption, etc.), which are very useful for those who operate such equipment, as well as for agricultural tractor dealers.

Keywords: *Plow, Agricultural tractor, Experimental testing, Quality indices, Energy indices.*

Introduction

Plowing is an essential, yet fuel-intensive agricultural task that requires careful adjustment of the plough to match the varying physical and mechanical characteristics of the soil across different plots, with variable plowing width and high-power tractors being recommended to optimize the adaptation to soil conditions and minimize the number of passes needed for large-scale operations. Enhancing the traction performance and power transfer efficiency of farm tractors during cultivation can lead to optimized energy utilization and reduced fuel consumption and greenhouse gas emissions (Md-Tahir, H., et. al., 2021), (Lekavičienė, K., 2019). Over the years, there have been numerous attempts to develop mathematical models that quantify the influence of the constructive and functional parameters of the plough on soil processing performance, considering its varying physical properties (Ghereș, M.I., 2013), (Gheorghiță, N.E., et. al., 2022), (Meca, V.A., 2012), (Augustin, K., 2019). Soil-machine interaction studies aim to provide scientific insights into how tillage tools and traction devices interact with the terrain, investigating variables such as pulling or pushing forces, vertical and lateral forces, soil failure patterns, displacement of soil particles, interface force between wheel and soil, wheel slippage, rolling resistance, estimation of wheel contact area, and soil stress at various depths. Soil bin facilities serve as ideal laboratories for tillage and traction

experiments, comprising components such as a soil bin simulating the ground, a mobile tool carrier representing tool frames, soil-engaging devices simulating tillage tools or traction elements, a power source and drive system emulating prime movers, soil conditioning equipment for soil preparation, motion control systems for component movement, measurement and data acquisition systems for real-time analysis, and a lifting system for heavy component handling (Ani, O. A., 2018), (Kheiralla, A.F., 2004), (Varani, M., 2023).The operational performance of the plough and the aggregate formed by it with a high-power tractor can be quantified in terms of qualitative and energetic indices, which are as follows (Gill, W.R., Vanden Berg, G.E., 1968):
The average working depth:

$$a_m = \frac{\sum_1^n a_i}{n} \text{ [cm]} \quad (1)$$

where: a_i -represents the measured working depth, (cm); n -the number of measurements.
Squared average deviation of working depth:

$$\sigma_a = \pm\sqrt{\frac{\sum_1^n (a_i - a_m)^2}{n-1}} \text{ [cm]} \quad (2)$$

The working depth variation index:

$$V_a = \frac{\sigma_a}{a_m} 100 \text{ [\%]} \quad (3)$$

The average working width:

$$B_m = \frac{\sum_1^n B_i}{n} \text{ [m]} \quad (4)$$

where: B_i - is the measured working width, (m); n -the number of measurements.
Squared average deviation of working width:

$$\sigma_B = \pm\sqrt{\frac{\sum_1^n (B_i - B_m)^2}{n-1}} \text{ [cm]} \quad (5)$$

The working width variation index:

$$V_B = \frac{\sigma_B}{B_m} 100 \text{ [\%]} \quad (6)$$

The degree of crop residue coverage: It is determined by the ratio, expressed as a percentage, between the amount of plant material remaining on the soil surface and the plant mass present on the field surface before the passage of the implement, using the following relationship:

$$G_v = \frac{\sum_1^n \frac{G_{ti} - G_{Si}}{G_{ti}}}{n} \times 100 \text{ [\%]} \quad (7)$$

where: G_{Si} - is the measured mass of plant residues remaining on the soil surface, on the sample taken, after the passage of the machinery, (g); G_{ti}- is the total measured mass of plant residues on the soil surface before the passage of the machinery, (g); n - the number of measurements.
The degree of soil pulverization: It represents the weight proportion of soil fractions with satisfactory fragmentation, namely with clod sizes of maximum 100 mm, relative to the total mass of the soil sample. It is calculated using the following relationship:

$$G_{ms} = \frac{\sum_1^n \frac{M_{ci}}{M_{ti}}}{n} \times 100 \text{ [\%]} \quad (8)$$

where: M_{ci} - the measured mass of soil clods with dimensions smaller than 100 mm, (kg); M_{ti} - the measured weight of the entire soil sample, (kg); n - the number of measurements.
Viteza de lucru:

$$v_e = \frac{3{,}6 \cdot s}{t} \text{ [km/h]} \quad (9)$$

where: s - linear distance traveled, (m); t - time taken to traverse the distance, (s).
Fuel consumption:

$$Q = \frac{V}{3{,}6t} \text{ [l/h]} \quad (10)$$

where: V -is the volume of fuel recorded by the consumption device, (ml); t -sampling time, (s).

Fuel consumption per hectare:

$$q=\frac{Q}{W_{ef}} \quad [1/ha] \tag{11}$$

where: Q -hourly fuel consumption, (l/h); W_{ef} -hourly effective working capacity, (ha/h).

The hourly working capacity during actual time:

$$W_{ef}=0,1\cdot B_m \cdot v \quad [ha/h] \tag{12}$$

where: B_m -is the average working width, (m); v -is the actual working speed, (km/h).

Material and Methods

The variable-plowing width for high-power tractors is designed to perform plowing on flat or sloping terrain of up to 6°, on all types of soil, at a maximum working depth of 30 cm. The plough operates in conjunction with 180-240 HP wheel tractors equipped with Category III SR ISO 730-1+C1 suspension mechanism. Field trials, under operating conditions, of the PP5VM plough in combination with a "Zimbru" type tractor with 195 HP (Fig. 1), were conducted in August 2022, on the lands of a family farm in Argeș County (Romania). The experimental field tests were carried out under the following conditions:

- soil type: brownish red with loamy-clay texture;
- previous crop: mechanically harvested wheat, with straw baled and transported immediately after harvesting; height of crop residues: 15 cm;
- mass of crop residues: 70 g/m²;
- soil moisture at a depth of 25-30 cm: 18%.
- The main characteristics of the plough used for experimental trials are: number of bodies: 5; diameter of the metal wheel: 500 mm; working width per body: 30-45 cm; distance between bodies in the forward direction: 830 mm; clearance under the frame: 780 mm; length: 4815 mm; width: 2670 mm; height: 1425 mm; constructive weight: 1400 kg.
- The main functional characteristics of the plough are: maximum working depth: 30 cm; clearance in transport: 600 mm; working speed: 4.5-9 km/h; transport speed: max 10 km/h. The constructive characteristics of the body are: share type: helical; maximum working depth: 30 cm; angle formed by the share edge with the furrow wall: 44^0 ; minimum angle of the generatrices with the furrow wall: 29^0 ; maximum angle of the generatrices with the furrow wall: 46^0 ; maximum height of the share above the furrow edge: 435 mm.



Fig. 1. The 195 HP "Zimbru" tractor and the plough with variable working width with 5 mouldboards.

Results and Discussion

In Table 1, the performance indicators of the aggregate consisting of the T195 tractor and the PP5VM plow are presented for plowing work at a depth of 30 cm and a furrow width of 40 cm on brown-red soil with average moisture of 18% in the plowed layer. In Table 2 and in Figure 2, qualitative indices of the plowing work performed with the aggregate consisting of tractor T195 and plough PP5VM on brown-reddish soil with an average moisture content of 18% in the plowed layer are presented. The meaning of the terms in the table is as follows: Working width on the mouldboard b_t(cm); Effective working speed v_e(km/h); Average working depth a_m(cm); Maximum deviation from $a_m \pm \Delta_a$(cm); Standard deviation σ_a(cm); Depth working inconsistency V_a(%); Average working width B_m(cm); Standard deviation σ_B(cm); Width working inconsistency V_B(%); Soil fragmentation degree G_{ms}(%); Vegetative residue coverage degree G_v(%).

Table 1. Performance indicators

Exploitation index name	**Symbol**	**U.M.**	**Value**
Operational time utilization coefficient	K_{02}	-	0.939
The coefficient of utilization of total operating time	K_{03}	-	0.890
Production time utilization coefficient	K_{04}	-	0.866
The utilization coefficient of exchange time	K_{07}	-	0.731
Return coefficient	K_{21}	-	0.942
Technological safety coefficient	K_{41}	-	0.993
Technical safety factor	K_4	-	0.970
Hourly working capacity at actual time	W_{ef}	ha/h	1.165
The hourly operational working capacity	W_{02}	ha/h	1.094
Hourly work capacity at total operating time	W_{03}	ha/h	1.037
Hourly work capacity during production time	W_{04}	ha/h	1.009
The hourly work capacity during the shift time	W_{07}	ha/h	0.851
The working capacity for an 8-hour shift	W_{sch}	ha/sch	6.813
Specific fuel consumption	Q	l/ha	27.56

Table 2. Qualitative indicators

b_t (cm)	v_e (km/h)	a_m (cm)	$a_m \pm \Delta_a$ (cm)	σ_a (cm)	V_a (%)	B_m (cm)	σ_B (cm)	V_B (%)	G_{ms} (%)	G_v (%)
30	8.04	19.7	2.4-3.6	1.88	6.65	156	11.8	5.49	85.8	85.6
	7.85	25.1	1.8-3.2	1.77	6.23	154	12.3	4.83	83.4	89.3
	7.38	29.7	1.7-2.9	1.73	5.95	153	11.5	4.39	80.2	93.4
35	7.87	20.1	2.1-3.2	1.85	6.53	186	10.9	5.93	84.3	88.6
	7.45	24.9	1.8-3.1	1.79	6.11	182	11.2	5.22	82.4	91.5
	6.83	30.2	2.2-3.3	1.76	5.84	181	10.5	4.11	80.3	94.3
40	7.42	19.9	2.3-3.7	1.89	6.66	220	11.6	6.08	82.3	94.3
	6.36	24.8	1.9-4.1	1.78	6.13	211	11.4	5.45	81.6	94.6
	5.42	30.1	2.4-3.6	1.83	5.81	215	11.3	4.77	79.8	95.2
45	7.01	20.2	2.5-3.8	1.92	6.84	243	12.6	6.37	79.6	96.5
	6.17	25.3	2.2-4.2	1.83	6.45	241	12.8	5.85	78.9	96.8
	5.14	29.6	2.7-4.5	1.87	5.98	234	12.5	5.32	78.3	95.9

In Table 3 and in Figure 3, the energy indices resulting from the experimental trials of the unit consisting of the T195 tractor and the PP5VM plough are presented for plowing work on brownish-red soil with an average moisture content of 18% in the plowing layer. The significance of the terms in the table is as follows: Working width per mouldboard b_t(cm); Average working depth a_m(cm); Average total working width B_m(cm); Average slippage δ

(%); Effective working speed v_e(km/h); Hourly fuel consumption q (l/h); Working productivityat effective time W_{ef}(ha/h); fuel consumption per hectare Q (l/ha).

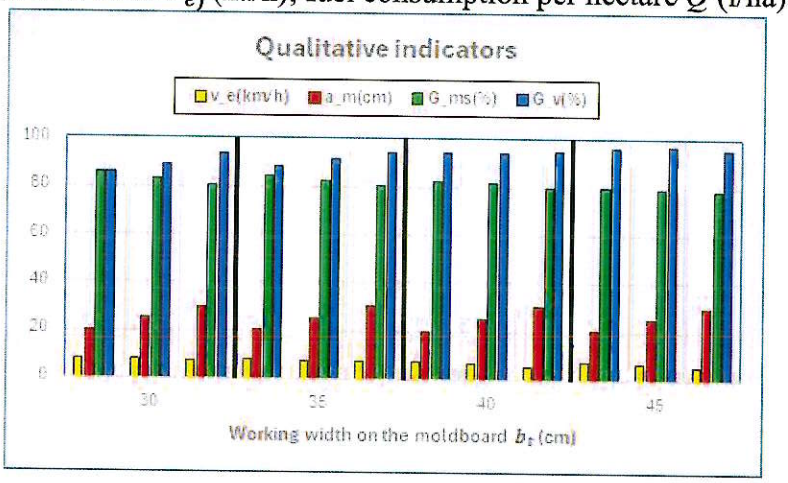


Fig. 2. The variation of quality indices depending on the width of the mouldboard

Table 3. Energy indices

b_t (cm)	Indices of working regime		The characteristic indices for adhesion, dynamics, and energetics			Productivity and consumption indices	
	a_m (cm)	B_m (cm)	δ (%)	v_e (km/h)	q (l/h)	W_{ef} (ha/h)	Q (l/ha)
30	19.7	156	11.8	8.04	29.53	1.254	23.54
	25.1	154	11.7	7.85	29.57	1.209	24.45
	29.7	153	12.1	7.38	30.15	1.129	26.70
35	20.1	186	11.9	7.87	29.85	1.464	20.39
	24.9	182	12.2	7.45	31.18	1.356	22.99
	30.2	181	12.3	6.83	31.79	1.236	25.72
40	19.9	220	12.8	7.42	30.12	1.632	18.45
	24.8	211	13.1	6.36	31.97	1.342	23.82
	30.1	215	13.5	5.42	32.11	1.165	27.56
45	20.2	243	13.9	7.01	32.25	1.703	18.93
	25.3	241	14.3	6.17	33.75	1.487	22.69
	29.6	234	15.5	5.14	34.55	1.203	28.72

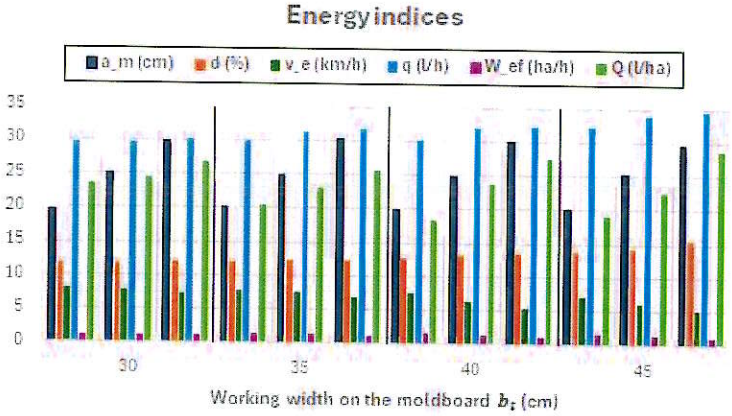


Fig. 3. The variation of energy indices depending on the width of the mouldboard

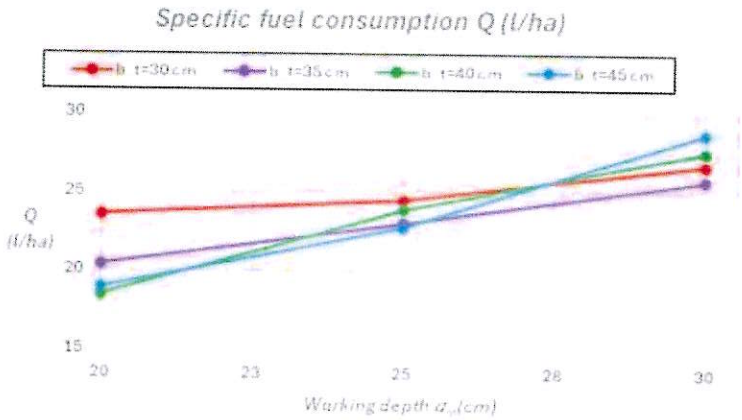


Fig. 4. The variation of specific fuel consumption depending on the working depth

In Figure 4, the graph shows the variation of specific fuel consumption as a function of plowing depth and adjusted working width for a single mouldboard. It can be observed that, as expected, the greatest variation in specific fuel consumption occurs when the working width on the mouldboard is the largest, i.e., b_t=45 cm. This variation is significantly smaller when the plough is adjusted so that the working width on the plow body is 30 cm. However, as indicated in Table 3 and Figure 3, the adjustments made to the plough and operating conditions allow for plowing work to be carried out such that wheel slip remains reasonable (within the range of 11-15%).

Conclusions

This paper emphasizes the essential role of plowing in agriculture, highlighting its irreplaceable nature due to high fuel consumption compared to other tillage methods. The effectiveness of variable plowing width is underscored, adapting efficiently to varying soil physical and mechanical characteristics and tractor traction performance. It recommends high-power tractors to minimize passes over fields, enhancing operational efficiency. Results from experimental trials in Romania using a variable plough width attached to a 200 HP tractor provide valuable data on qualitative and energy indices, such as fuel consumption and tractor efficiency, beneficial for equipment operators and agricultural tractor dealers.

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A MATHEMATICAL ALGORITHM FOR THE CALCULATION OF THE OPTIMUM TIME FOR USING OF AN AGRICULTURAL MACHINE

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Abstract: *This paper presents a mathematical algorithm that can be very useful to farmers and agricultural machinery manufacturers, which allows the optimal time to be used for all agricultural machines to be calculated so that the profit is maximum, depending on the initial purchase price, on the costs the depreciation of the investment, the cost of repairing the equipment, the quality of the equipment, and the nature of the agricultural work carried out.*

Key words: *Agricultural machine, Mathematical algorithm, Optimization, Profit, Optimum time.*

INTRODUCTION

It is known that agricultural machinery has an optimal time for efficient use. It depends on a number of factors, such as the cost of equipment acquisition, the cost of equipment damping and repairs, the quality of the machine, etc. [Şandru, A. et al. 1983]. All of these factors influence the profit that a machine can generate. In particular, in the case of developing countries, the quality of the equipment purchased is lower and the tendency for them to be used for a much longer period of time, seriously affecting the profits they generate, mainly due to repair costs [Hunt, R.D. 1986, Bold, I., Crăciun, A. 1995]. It is necessary to investigate the elaboration of mathematical models that allow the estimation of the optimal time for using the agricultural equipment for different specific exploitation conditions [Allire, G., Boyer, R. 1995].

To establish an optimal machinery system and an optimal mechanization technology for different types of agricultural farm and for various specific conditions it is necessary to use scientific methods of optimization [Moise et al. 2010, Otiman, P.I. 1997]. The success of a business, including agriculture, is determined by the amount of profit, which depends on the quality and quantity of the realized product [Hunt, R.D. 1986].

Optimization methods have become indispensable in making a correct decision on the solution to be adopted in making a product. If by the appearance of an elevated mathematical device, decisions could be arbitrary or empirical, with the emergence of optimization methods decision became objective and scientifically proved [Hunt, R.D. 1986]. Thus, optimization methods offer the selection process of the optimal solution from the multitude of admissible solutions, a solution that meets the requirements and leads to the best result [Moise et al. 2010].

The major objective of this paper is to present a mathematical algorithm that can be very useful to farmers and agricultural machinery manufacturers, which allows the optimal time to be used for all agricultural machines to be calculated so that the profit is maximum, depending on the initial purchase price, on the costs the depreciation of the investment, the cost of repairing the equipment, the quality of the equipment, and the nature of the agricultural work carried out.

MATERIAL AND METHODS

The optimal time for using an agricultural machine T_0 can be determined by the fact that the average annual expenses with amortization and its maintenance and repair are minimal, respectively by minimizing the function:

$$Y = Y_1 + Y_2 = \frac{\delta(1+\delta)^T C_a}{(1+\delta)^T - 1} + \frac{C_{IR}(T)}{T} \quad (1)$$

in which $C_{IR}(T)$ it represents the cost of maintenance and repairs in T years, T being an independent variable.

The Y function results from the summation of functions Y_1 and Y_2 which are the sum of the annual average amortization function corresponding to the initial cost of the aggregate and the average annual amortization of its maintenance and repairs, as shown in Figure 1.

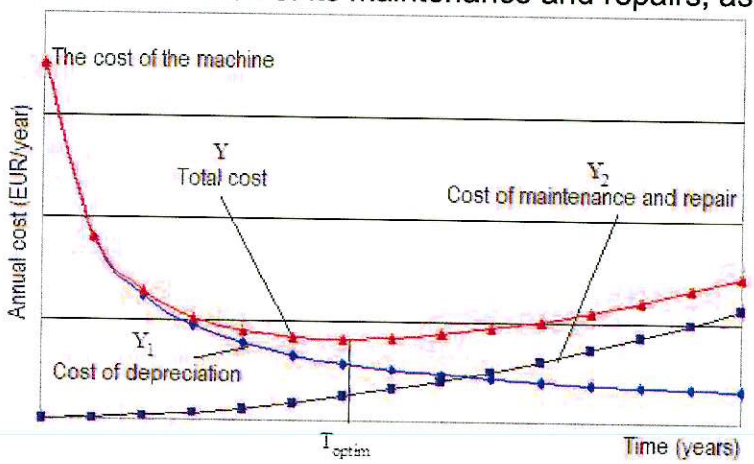


Fig. 1. *How to determine the optimal time for using a machine.*

The total cost of maintenance and repairs C_{IR} over a *T*-year period varies over time. This cost can be determined with the relationship:

$$C_{IR}(T) = \int Y_{IR}(T)dT \quad (2)$$

where $Y_{IR}(T)$ it is the function which then varies with the annual cost of maintenance and repairs. This function can be approximated by a parabolic function, ie these costs are increased even more so as the aggregate is used for a longer period *T*. Therefore, considering that the parable passes by origin, respectively $Y_{IR} = AT^2$, we will have:

$$C_{IR}(T) = \int A \cdot T^2 dT = \frac{AT^3}{3} \quad (3)$$

where *A* is a coefficient that can be determined from the condition that at *T* = 10 years. In this case the relation (2) results:

$$\varphi C_a = \int_0^{10} A \cdot T^2 \mathrm{d}T = \frac{A \cdot T^3}{3}\Big|_0^{10} = \frac{1000A}{3} \quad (4)$$

from which it is determined:

$$A = \frac{3\varphi C_a}{1000} \quad (5)$$

Taking into account the relation (5), relation (2) becomes:

$$C_{IR}(T)=\int_0^T \frac{3\varphi C_a}{1000}T^2 dT=\frac{\varphi C_a}{1000}T^3 \quad (6)$$

Introducing the above relationship into (1) results:

$$Y=\frac{\delta(1+\delta)^T C_a}{(1+\delta)^T-1}+\frac{\varphi C_a T^2}{1000} \quad (7)$$

in which: C_a- represents the cost of the damping machine; δ - the interest rate; φ - represents the ratio of the maintenance and repair costs of a machine over a period of 10 years to the cost of purchasing it; T - the machine's use time, and which represents the function variable.

The optimum use time of the aggregate T_0 for a certain coefficient φ is determined by minimizing the equation (7).

The optimal use time of the aggregate, using the analytical method, for a certain coefficient φ, results from the zeroing of the derivative of the function (3) in relation to T, respectively:

$$\frac{dY}{dT}=2\varphi T[(1+\delta)^T-1]^2-1000\delta(1+\delta)^T\ln(1+\delta)=0. \quad (8)$$

Given the complexity of the derivative of the function (7), solving the equation (8) can be done numerically, using the methods of solving the nonlinear equations. The solution of this equation will correspond to $T_{optim}=T_{0\,(\delta\neq 0)}$ which is a function of φ. But, as the function φ depends on the quality x after a function $\varphi=\varphi(x)$, similar to the change of the function $T=T(\varphi)$, with different coefficients, the function $T=T(x)$ can be established by deleting the variable φ the two functions.

As a result, the optimum running time of the machine will be $T_{optim}=T_0=T_0(x)$.

The analytical function $T_0=T_0(x)$ will result indirectly from the maximization or minimization of the purpose function (relation 7), where x is one of the independent variables.

In the particular case, when δ=0, removing the non-determination from the first term, with L'Hospital's rule, the relationship (7) becomes:

$$Y=\frac{C_a}{T}+\frac{\varphi C_a T^2}{1000}, \quad (9)$$

The optimal time T_0 for the use of the aggregate in the considered case (δ=0 and φ=const.) Results from the minimization of the function given by the relation (6), respectively:

$$\frac{dY}{dT}=-\frac{C_a}{T^2}+\frac{2\varphi C_a T}{1000} \quad (10)$$

from which it follows:

$$T_{opt}=T_{0(\delta=0)}=\sqrt[3]{\frac{1000}{2\varphi}} \quad \text{[years]} \quad (11)$$

where φ is a function of the x quality of the considered machine.

If we have the average rates of damping equal and settled each year, the optimum use time of the aggregate can be approximated as:

$$T_{optim}=T_0=\frac{1}{2}(T_{0(\delta\neq 0)}+T_{0(\delta=0)}) \quad \text{[years]} \quad (12)$$

RESULTS AND DISCUSSION

For the application of the calculation algorithm (relation 7) 4 different situations (4 machines with different characteristics) were used, as shown in Table 1.

Table 1. *The technical and economic characteristics of the four agricultural machines used for the analysis.*

Case	Parameters		
	C_a (EUR)	φ	δ
1	10000	1.5	0.05
2	10000	0.5	0.05
3	20000	1.5	0.05
4	20000	0.5	0.05

The variation curves of depreciation cost, repair cost and total cost of the four agricultural machines used for the analysis are shown in Figure 2.

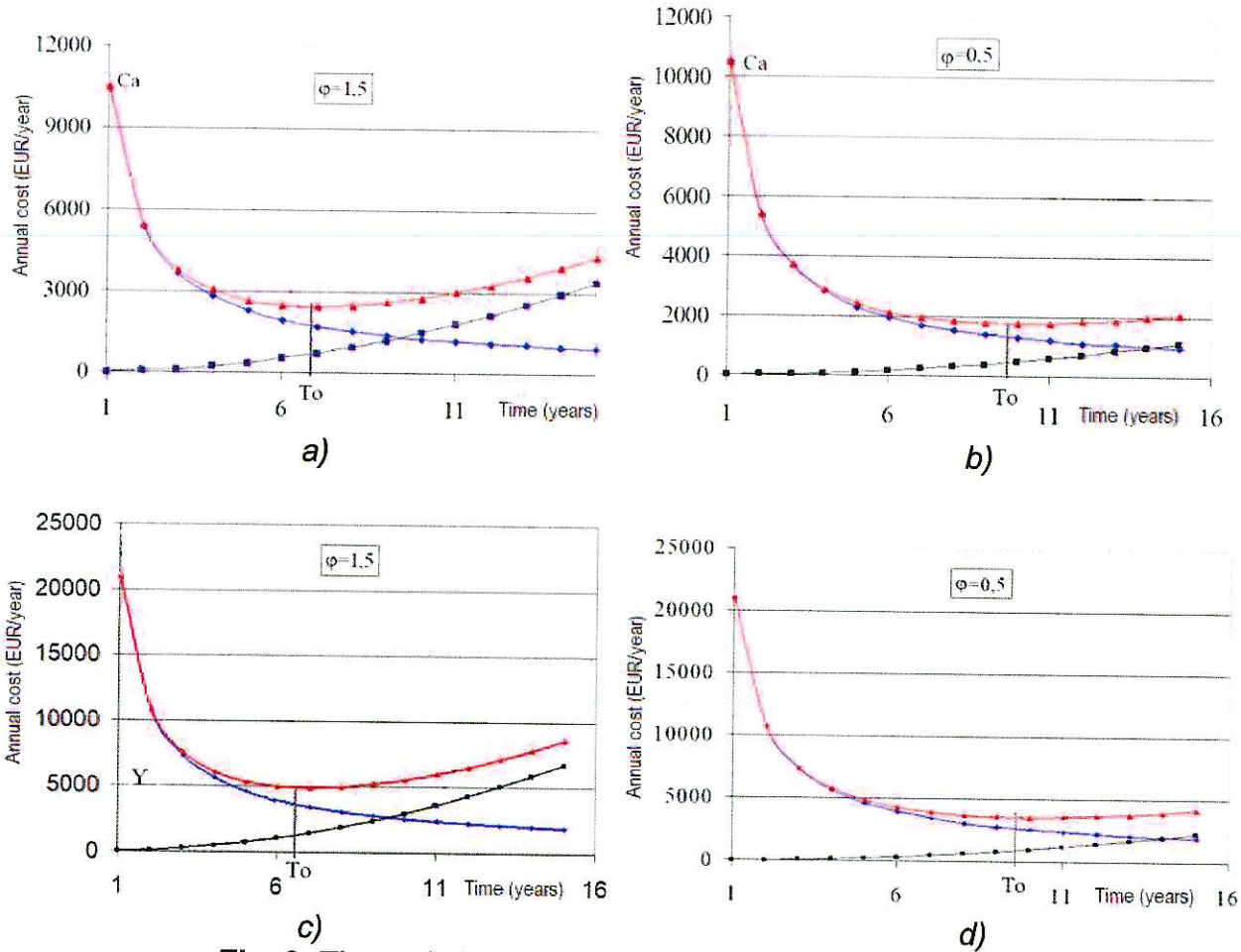


Fig. 2. *The variation curves of depreciation cost, repair cost and total cost of the four agricultural machines.*
a) C_a=10000 EUR, φ =1.5; b) C_a=10000 EUR, φ =0.5;
c) C_a=20000 EUR, φ =1.5; d) C_a=20000 EUR, φ =0.5

In figure 2, it can be seen that the variation in the total cost Y around the point corresponding to T_0 is much more pronounced for low values of T_0 and is much slower around the high values of T_0, which means that good quality machines can be used for a time $T>T_0$, without significantly increasing the total cost. The same can not be accepted for poor quality machines for which φ is higher, in which case their use over time T_0 leads to considerable losses.

There may be cases at the same price for agricultural machines of different qualities, but the free market decides in favor of better quality ones. There are situations where, according to a good project, the same machine is manufactured by different qualities by not complying with the documentation, but is sold at the same price. In this case, the total cost differs considerably according to the value of the coefficient φ, the damages reflecting the buyer in the operation of the machine.

CONCLUSIONS AND FUTURE WORK

The optimal time T_0 does not depend on the initial cost of the machine but only on the coefficient φ. By derivating the function from the relation (7) and equalizing the derivative with zero it simplifies C_a.

Total expenditures, corresponding to the optimal time T_0, increase with the increase of the initial cost of the agricultural machinery C_a and with the increase of the coefficient φ.

Optimal time T_0 increases with decreasing coefficient φ, respectively, for better quality machines.

The variation in the total cost Y around the point corresponding to T_0 is much more pronounced for low values of T_0 and is much slower around the high values of T_0, which means that good quality machines can be used for a time $T>T_0$, without significantly increasing the total cost.

There may be cases at the same price for agricultural machines of different qualities, but the free market decides in favor of better quality ones.

The most common situation is when the buyer has to decide between a good quality machine but a lot more expensive and a lower quality but cheaper machine.

This algorithm allows the optimal time to be used for all agricultural machines to be calculated so that the profit is maximum, depending on the initial purchase price, on the costs the depreciation of the investment, the cost of repairing the equipment, the quality of the equipment, and the nature of the agricultural work carried out

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THEORETICAL RESEARCH ON IMPROVING THE PERFORMANCE OF A 65 HP AGRICULTURAL TRACTOR USED FOR HARROWING OPERATIONS

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In this paper a theoretical study is presented which, based on a dynamic model of the tractor-agricultural machine system, a mathematical model and a computational algorithm, makes an important contribution to the theoretical estimation of the traction performance and the increase of this performance (driving force, specific driving force, coefficient of adhesion weight utilization, rolling resistance force of the agricultural tractor, draft force) for a 4x2 tractor of 65 HP type, used in soil tillage with a mounted disc harrow rather than the semi-mounted version as is commonly used.

Keywords: disc harrow, tractor dynamics, soil, resistive force.

1. Introduction

It is well known that tillage for seedbed preparation is the most fuel-consuming of all agricultural works. Disc harrow tillage is one such tillage and can be used for soil fragmentation after ploughing or for conservation tillage, replacing ploughing under certain conditions.

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Numerous theoretical and experimental studies have been carried out over the years in order to identify the optimal operating conditions of the tractor and disk harrow aggregate used for processing soil after plowing for fragmenting. Such a study presents the results obtained from experimental field trials of a tractor-disc harrow system, which provide dependency relationships between operating conditions, tillage quality indices and energy indices, for two different soil types [1].Compared to cultivators, the use of disc harrows is more advantageous, especially where the volume of plant residues is higher, because it is possible to cut the stems of plant residues and avoid clogging of the machine, with lower energy consumption [2]. In these conditions with higher volume of plant residues in the soil to be processed, it has been proved that disc harrows are more versatile and can be used in a wider variety of conditions compared to other soil tillage machines [3].

At the same time, the danger of artificial compaction of agricultural soil is present in tillage systems, which greatly affects plant growth, soil water infiltration and cultivation costs. Optimal exploitation of the tractor-disc harrow system for prevention of soil compaction and carrying out agricultural tillage with maximum quality indices under energy-efficient conditions is a continuous challenge of researchers in this field [4, 5].

Over the years, several researchers have tried to develop both theoretical and empirical computational models for estimating the power consumed for soil tillage in the harrowing operation, depending on the physical-mechanical properties of the soil, soil humidity, working depth and working speed [6, 7]. To this end, mathematical models based on regression equations have been developed to estimate the draft force and power consumed with working speed and depth as independent variables [8].

In order to increase the efficiency of soil tillage with disk harrows, experimental research has been carried out to develop technical solutions for harrow construction, more suitable for working at different soil moisture contents [9], more adapted for cutting plant residues [10], more adequate to ensure an efficient trajectory of soil particles in contact with the disk and the lowest energy consumed for transporting the soil furrow [11].

As the working parts of agricultural soil tillage machines, including disc harrows, are subject to a pronounced wear process as a result of interaction with the soil, great attention has been paid to the choice of materials from which these working parts are made, as well as to the special heat treatments they are subjected to, or to the deposits of wear-resistant materials in the area of the disc edge [12].

In recent years, there has been an increasing emphasis on the development of computational models for advanced assessment of tractor performance in aggregate with a towed disk harrow [13] and, in particular, of mechanical models that allow the calculation of the reactions on the tractor wheels and disk harrow so

that the draft force and the optimal redistribution of these reactions can be estimated and the tractor's draft performance can be increased [14].

The main objective of this study is to develop calculation algorithms for the front and rear wheel reactions of a 65 HP 4x2 tractor coupled with a disc harrow, in two coupling configurations: (1) semi-mounted and (2) fully-mounted, in order to identify and improve the tractor's draft performance under various soil and operating conditions.

2. Dynamics of the Tractor–Disc Harrow System

During operration, the 4x2 tractor (U-650) (Fig. 1), is subjected to the following forces: tractor's weight G, the rolling resistant force R_r, rolling resistant moments M_{r1} și M_{r2}, driving force F_m, components F_t și R_z of the resultant force R transmitted to the tractor by the implement, and the reaction forces Z_1 și Z_2 at the front and rear axles, respectively. It is assumed that the tractor's weight G acts at its center of mass, defined by the coordinates a_c și h. The action of the implement on the 4x2 tractor can be replaced with the draft force (parallel to the ground surface) F_t and the normal component R_z (perpendicular to the ground surface The point of application of these two forces is defined by the coordinates l_t (relative to the rear axle axis) and h_t (relative to the ground surface).

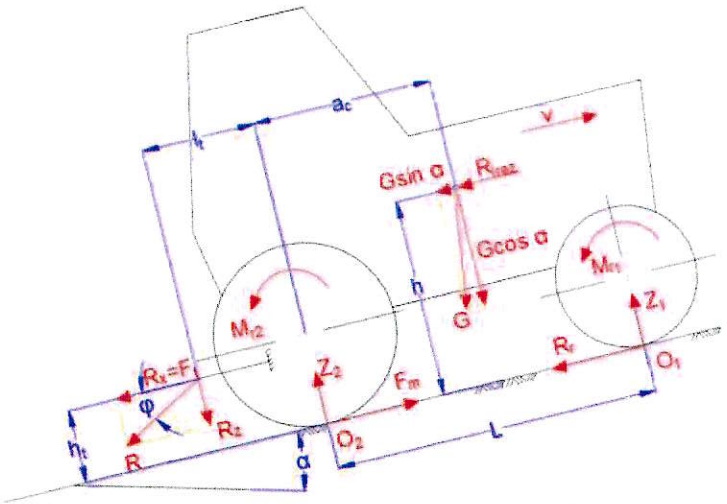


Fig. 1. Forces acting on a 4x2 tractor coupled with a trailed or semi-mounted implement [15]

In the case of the aggregate formed by a 4x2 tractor and a semi-mounted disc harrow (Fig. 2), the reactions Z_1 și Z_2 are determined based on the equilibrium equations of the tractor under the action of external forces, using the following relations [15]:

$$\begin{cases} Z_1 = [G \cdot a_c \cdot \cos\alpha - (G \cdot \sin\alpha + R_{irez}) \cdot h - F_t \cdot h_t - R_z \cdot l_t - M_r]/L \\ Z_2 = [G \cdot (L - a_c) \cdot \cos\alpha + (G \cdot \sin\alpha + R_{irez}) \cdot h + F_t \cdot h_t + R_z \cdot (L + l_t) + M_r]/L \end{cases} \quad (1)$$

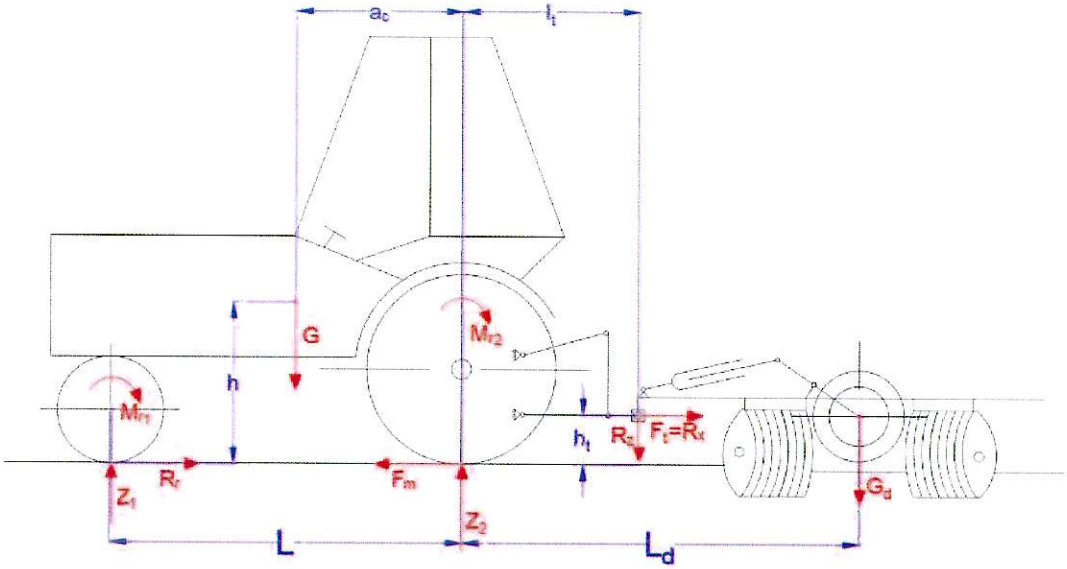


Fig. 2. Forces acting on a 4x2 tractor coupled with a semi-mounted disc harrow during operation

Total load Z_t acting on the tractor axles is given by the sum of the reactions on the two axles, namely::

$$Z_t = Z_1 + Z_2 = G \cdot \cos\alpha + R_z \quad (2)$$

The expression of the rolling resistance moment M_r in the system of equations (1) is determined as the sum of the rolling resistance moments on the two axles:

$$M_r = M_{r1} + M_{r2} = f_{r1} \cdot Z_1 + f_{r2} \cdot Z_2 \cong f_{r2} \cdot (Z_1 + Z_2) = f_{r2} \cdot Z_t = r_2 \cdot R_r \quad (3)$$

Where f_{r1} and f_{r2} are the front/rear wheel rolling coefficients and R_r is the total rolling resistance of the tractor:

$$R_r = f \cdot Z_t \quad (4)$$

If the moment M_r, which has small values, is neglected and it is considered that the tractor is moving on level ground at a constant speed, the reactions Z_1, Z_2 and Z_t are calculated using the following formulas [16]:

$$Z_1 = \frac{G \cdot a_c}{L} - \frac{F_t \cdot h_t + R_z \cdot l_t}{L} \quad (5)$$

$$Z_2 = \frac{G \cdot (L - a_c)}{L} + \frac{F_t \cdot h_t + R_z \cdot (L + l_t)}{L} \quad (6)$$

$$Z_t = Z_1 + Z_2 = G + R_z \quad (7)$$

In the case of an aggregate consisting of a 4x2 tractor (U-650) and a fully-mounted disc harrow (Fig. 3), during operation on level ground, the normal

reactions on the tractor's two axles and the total load are calculated using the following relations:

$$Z_1 = \frac{G \cdot a_c}{L} - \frac{G_d \cdot l_m + F_z \cdot l_r - F_x \cdot h_r}{L} \quad (8)$$

$$Z_2 = \frac{G \cdot (L - a_c)}{L} + \frac{G_d \cdot (L + l_m) + F_z \cdot (L + l_r) - F_x \cdot h_r}{L} \quad (9)$$

$$Z_t = Z_1 + Z_2 = G + G_d + F_z \quad (10)$$

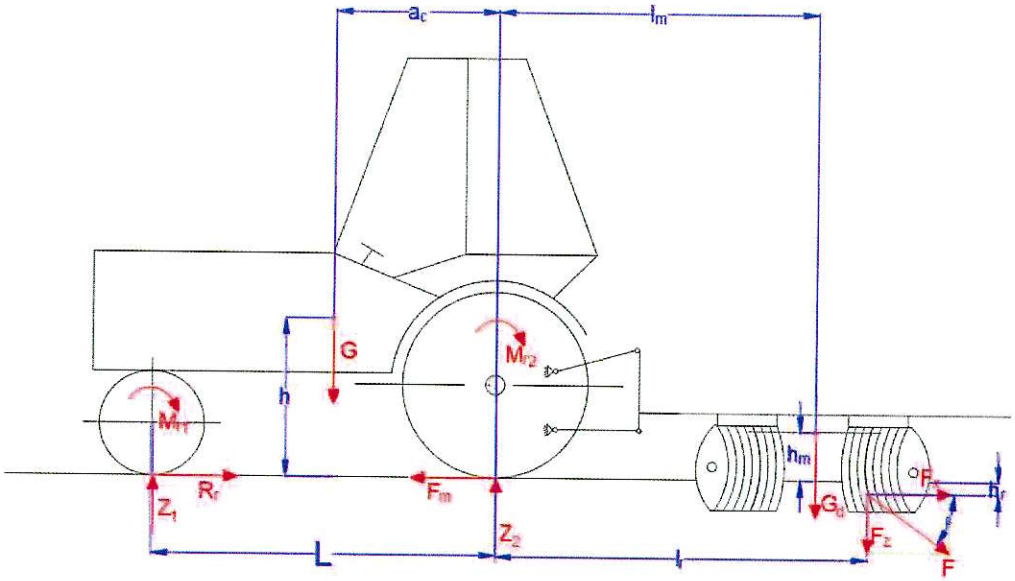


Fig. 3. Forces acting on a 4x2 tractor coupled with a fully-mounted disc harrow during operation

3. Calculation of the draft force of the U-650 tractor

The traction balance equation of a tractor operating in combination with an agricultural implement on level ground is [16]:

$$F_t = F_m - R_r \quad (11)$$

where F_m - represents the driving force (the tangential draft force), R_r -rolling resistant force, and F_t -draft force.

For any driving wheel operating on different soil types, the maximum tractive force and the maximum wheel efficiency are developed under specific vertical loads. The parameter that most accurately characterizes the slippage of tractor wheels is the specific driving force (φ_m) which represents the coefficient of utilization of the adhesive weight. It is defined as the ratio between the driving force F_m of the drive wheel (or drive axle) and the vertical reaction Z_m on the drive wheel (or axle):

$$\varphi_m = \frac{F_m}{Z_m} \quad (12)$$

For a firm plowed soil surface on which the tractor operates in combination with the disc harrow, the coefficient of utilization of the adhesive weight is φ_m=0.4÷0.6. Therefore, the expression of the driving force as a function of the vertical load on the drive axle is:

$$F_m = \varphi_m \cdot Z_m \tag{13}$$

The rolling resistance force of the agricultural tractor is calculated using the following relation:

$$R_r = f \cdot (Z_1 + Z_2) \tag{14}$$

where: f - represents the rolling resistance coefficient of the tractor (f=0.12-0.14 - for a flat ploughed terrain), Z_1 and Z_2 - represents the reactions at the two axles (front and rear).

The reactions Z_1 and Z_2 are dependent on the tractor weight G, the weight of the disc harrow G_d, the coordinates of the tractor and disc harrow centers of gravity, the tractor wheelbase, and the draft force F_t, as shown in equations (5), (6), (8) and (9).

The slippage of the drive wheels depends on the magnitude of the draft force F_t, the load on the driving wheel Z_m, the type and condition of the ground surface, the shape and size of the tires. Figure 4 presents the slip characteristic of the U-650 tractor on the tilled soil, for which a regression equation was also derived by a second-degree interpolation function that expresses the relationship between tractive force and wheel slip. For optimal operation of the tractor–implement system, it is recommended that the wheel slip remain within the range of 10–20% [17]. Therefore, as shown in Fig. 4, or the U-650 tractor operating on tilled soil, the recommended tractive force values are in the range of 8.3-10.6 kN.

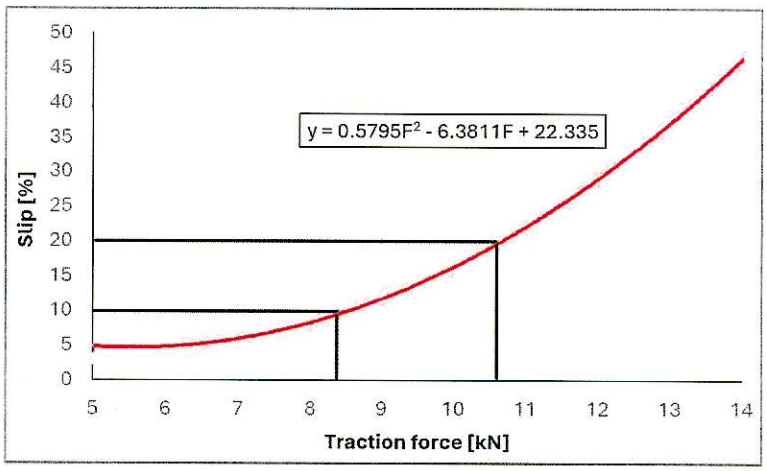


Fig. 4. Slip characteristic of the U-650 tractor on tilled soil [17]

In order to move the agricultural implement (in this case, the semi-mounted disc harrow), the tractor's tractive force must be greater than the resistance force

generated during the harrow's operation, which can be calculated using the following relation [15,16]:

$$R = K_s \cdot B_l \tag{15}$$

where: K_s - represents the specific resistance per unit working width during soil tillage using a disc harrow, (N/m); B_l - the working width of the disc harrow, (m). For smooth disc harrows, the specific resistance K_s typically ranges between 2÷3.25 kN/m [16]. In the case of fully-mounted disc harrows, the specific resistance K_s is 15–20% lower compared to that of trailed or semi-mounted implements [16].

4. Results and discussion

Given the importance of the specific resistance per unit working width in soil tillage using a semi-mounted disc harrow, and the fact that this resistance decreases by 20 % in the case of a fully-mounted harrow, Figure 5 presents a comparative view of the variation curves of the resistance force R, for the two disc harrow coupling configurations (semi-mounted – blue curve, and fully-mounted – orange curve), as a function of K_s.

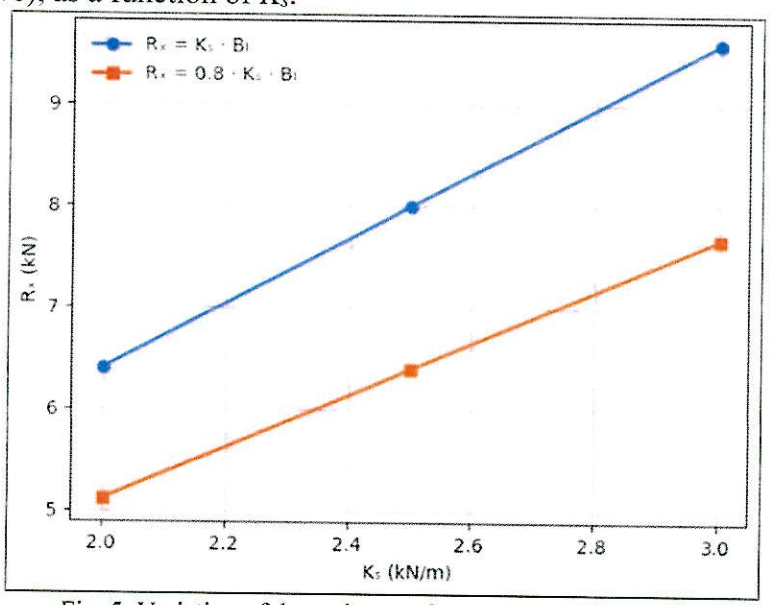


Fig. 5. Variation of the resistance force R as a function of K_s

Based on relations (5), (6), (8) and (9) a Python script was developed to calculate the normal reactions on the two axles of the U-650 tractor for the two coupling configurations of the disc harrow: semi-mounted (Z_{11} and Z_{12}), and fully-mounted (Z_{21} și Z_{22}). Figures 6 and 7 show the graphical variation of these reactions as a function of the specific resistance per unit working width K_s during soil tillage using the disc harrow.

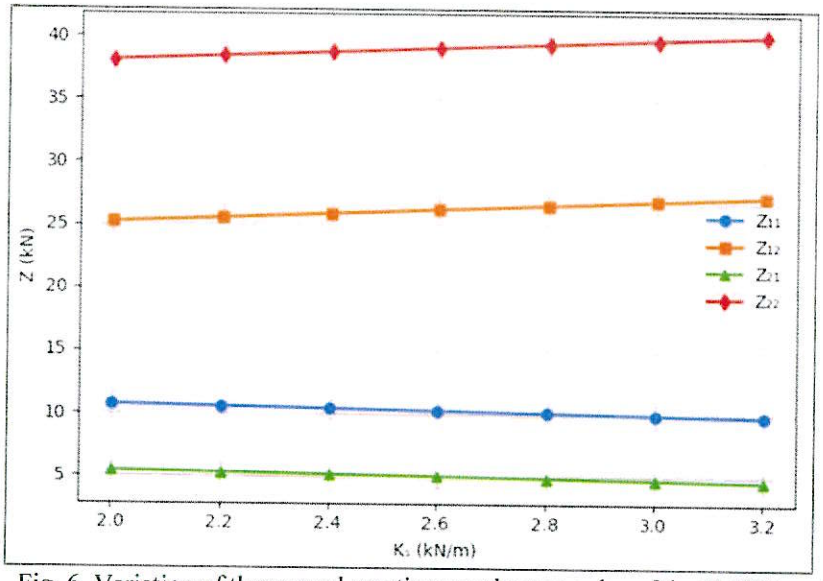


Fig. 6. Variation of the normal reactions on the two axles of the U-650 tractor as a function of K_s

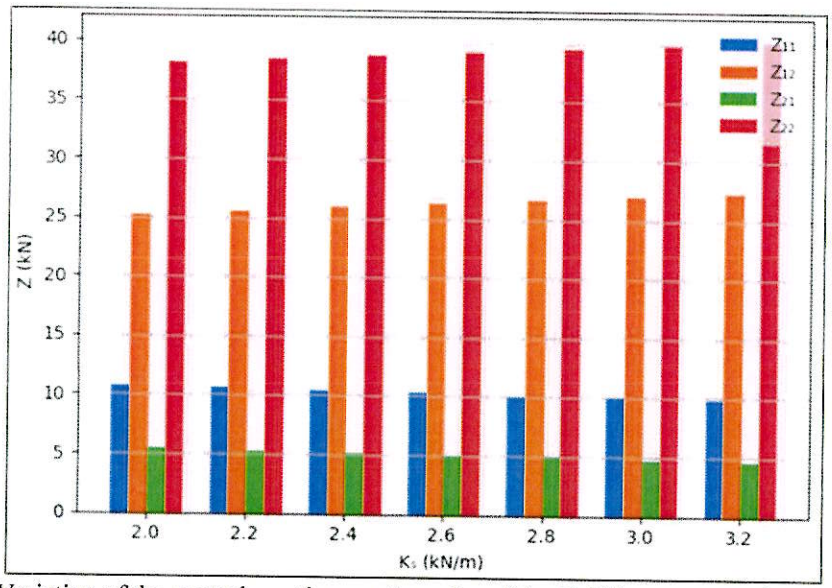


Fig. 7. Variation of the normal reactions on the axles of the U-650 tractor as a function of K_s

Taking into account the coefficient of utilization of the adhesive weight, which is calculated based on the vertical reaction on the drive axle according to relation (12), the driving force F_m was calculated using relation (13) for the U-650 tractor operating in combination with a semi-mounted and fully-mounted disc harrow on a firm plowed surface. The calculation results obtained using a Python script, along with the corresponding variation graphs, are presented in Figure 8.

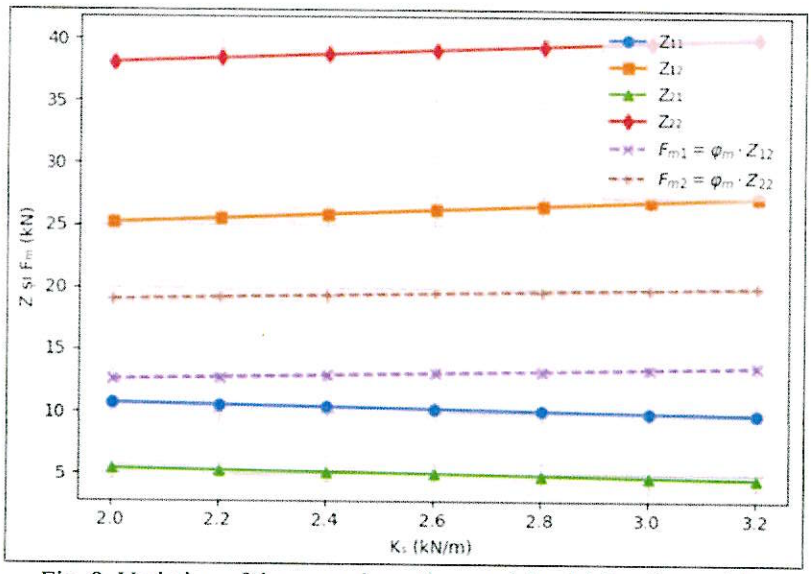


Fig. 8. Variation of the normal reactions and the driving force of the U-650 tractor as a function of K_s

```python
import matplotlib.pyplot as plt
import numpy as np
# Parametri constanți
G = 34     # kN
G_d = 7.6  # kN
L = 2.5    # m
B_l = 3.2  # m
a_c = 0.9  # m
l_t = 1.0  # m
l_r = 2.0  # m
l_m = 1.8  # m
h_t = 0.3  # m
h_r = 0.07 # m
fi_m = 0.5   # coeficient pentru F_m1 și F_m2
f = 0.13     # coeficient pentru R_r1 și R_r2
# Valorile lui K_s între 2 și 3.2 cu increment de 0.2
Ks = np.arange(2, 3.21, 0.2)
# Calculul funcțiilor Z
Z11 = (G * a_c - Ks * B_l * h_t - 0.3 * Ks * B_l * l_t) / L
Z12 = (G * (L - a_c) + Ks * B_l * h_t + 0.3 * Ks * B_l * (L + l_t)) / L
Z21 = (G * a_c - G_d * l_m - 0.3 * Ks * B_l * l_r + Ks * B_l * h_r) / L
Z22 = (G * (L - a_c) + G_d * (L + l_m) + 0.3 * Ks * B_l * (L + l_r) - Ks * B_l * h_r) / L
# Calcul F_m1 și F_m2
F_m1 = fi_m * Z12
F_m2 = fi_m * Z22
# Calcul R_r1 și R_r2
R_r1 = f * (Z11 + Z12)
R_r2 = f * (Z21 + Z22)
# Calcul F_t1 și F_t2
F_t1 = F_m1 - R_r1
F_t2 = F_m2 - R_r2
# Trasarea graficului comparativ
plt.plot(Ks, F_t1, marker='o', linestyle='-', label=r'$F_{t1} = F_{m1} - R_{r1}$')
plt.plot(Ks, F_t2, marker='s', linestyle='--', label=r'$F_{t2} = F_{m2} - R_{r2}$')
plt.xlabel('K_s (kN/m)')
plt.ylabel(r'$F_t$ (kN)')
plt.title('Comparație între funcțiile $F_{t1}$ și $F_{t2}$ în funcție de $K_s$')
plt.grid(True)
plt.legend()
plt.tight_layout()
plt.show()
```

Fig. 9. Python code for calculating the variation of the traction force of the U-650 tractor as a function of K_s for the two disc harrow coupling configurations (semi-mounted F_{t1} and fully-mounted F_{t2})

To calculate the traction force of the U-650 tractor in combination with a semi-mounted and a trailed disc harrow, depending on soil conditions and the cross-sectional area of the soil furrow processed in a single pass, as well as to generate a comparative graphical representation, a Python script was developed, as shown in Figure 9, and the graphical results are illustrated in Figure 10.

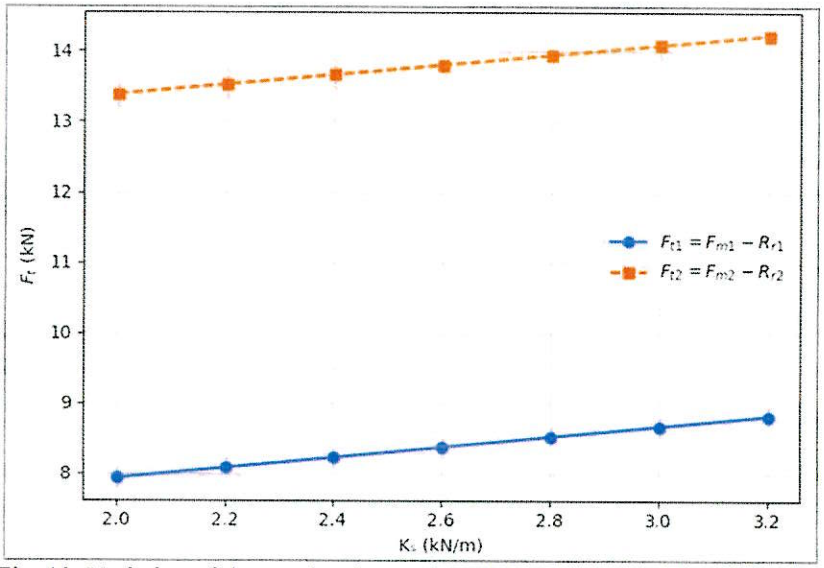


Fig. 10. Variation of the traction force of the U-650 tractor as a function of K_s for the two disc harrow coupling configurations (semi-mounted F_{t1} and fully-mounted F_{t2})

As can be seen in Figure 10, under the same working conditions, the draft force of the U-650 tractor increases significantly when the disc harrow is fully-suspended, due to the higher vertical reaction on the drive axle compared to the semi-suspended configuration, which also results in a considerable increase in the driving force. As shown in Figure 10, the draft force increases by approximately 25–35%.

5. Conclusions

Based on the dynamics of the technical system composed of a rear-wheel-drive tractor and two different types of disc harrows,one semi-mounted and one fully-mounted, a study can be developed to determine the axle reactions on the tractor for both coupling configurations. The mathematical models developed in this article are particularly important, as they allow for the theoretical estimation and improvement of the traction performance of a 4x2-type tractor when used in combination with a disc harrow in either a semi-mounted or fully-mounted configuration. These models enable the evaluation of the driving force, the specific

driving force, the coefficient of utilization of the adhesive weight, the rolling resistance force of the agricultural tractor, and the overall draft force.

In order to ensure the operation of the disc harrow during fieldwork, the tractor's traction force must exceed the resistance force generated by the harrow, which depends on the specific resistance per unit working width and the working width of the disc harrow. For smooth disc harrows coupled to the tractor in a semi-mounted configuration, the specific resistance per unit working width has values in the range of K_s=2÷3.25 kN/m, and in the case of fully-mounted disc harrows, the specific resistance is 15–20% lower compared to that of trailed or semi-mounted implements. Since the vertical load on the drive axle of the tractor increases when the disc harrow is coupled in the fully-mounted configuration, the driving force also increases, leading to a rise in the tractor's draft force by approximately 25–35%, and consequently to a reduction in fuel consumption required for soil tillage under the same working conditions.

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Article

CONTRIBUTIONS TO CREATING AN ALGORITHM OF CALCULATION OF OPTIMAL OPERATING PARAMETERS FOR A COMPLEX AGRICULTURAL MACHINE FOR SEED-BED PREPARATION

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Keywords: *agricultural machine, tillage, traction force, mathematical modeling, optimization*

Abstract: The execution of agricultural works in optimal operating conditions is imperative for the optimal management of energy resources and for obtaining maximum technological performance. Agricultural machines used for tillage are among the biggest consumers of energy. This paper presents a theoretical model and an optimization algorithm using the Newton-Raphson method and a source program written in Python that allows the determination of the optimal operating parameters of a complex agricultural machine for seed-bed preparation.

1. Introduction

Currently, the preparation of the germinal bed in order to sow crops is one of the most important agricultural works involving both high energy consumption and high costs [2, 14]. The degree of germination and the productivity of the crops depends on the quality of the seedbed preparation works [19, 27].

The execution of agricultural works in optimal operating conditions is imperative for the optimal management of energy resources and for obtaining maximum technological performance [22]. Agricultural machines used for tillage are among the biggest consumers of energy [23].

The combinator are agricultural machines featuring a variety of working bodies that grind, loosen, and level the top layer of soil in a sequential manner, and this equipment is used in soil tillage to prepare for sowing [3]. The benefits of using vibro-combinator include seedbed preparation under tough working conditions, moisture and overall porosity preservation, and a reduction in soil compression degree [5].

From the study of the specialized literature [2, 13, 14, 17] results the block diagram of the systemic representation of the tillage process, which is presented in Fig. 1.

The mathematical model of the total energy consumption is built on the basis of the dynamic model of the agricultural system shown in Fig. 2, being composed of a series of equations that highlight the way the system variables interact [4,17].

The experimental verification of the mathematical models is based on the scheme of the energy model of the agricultural system shown in Fig. 3. The total energy introduced into the agricultural system through the fuel used in order to carry out a work in the technology of preparing the germinal bed is consumed for: operating the internal combustion engine; losses from the tractor transmission; moving the tractor and the tiller; operating the tiller through the power take-off and traction [4,17].

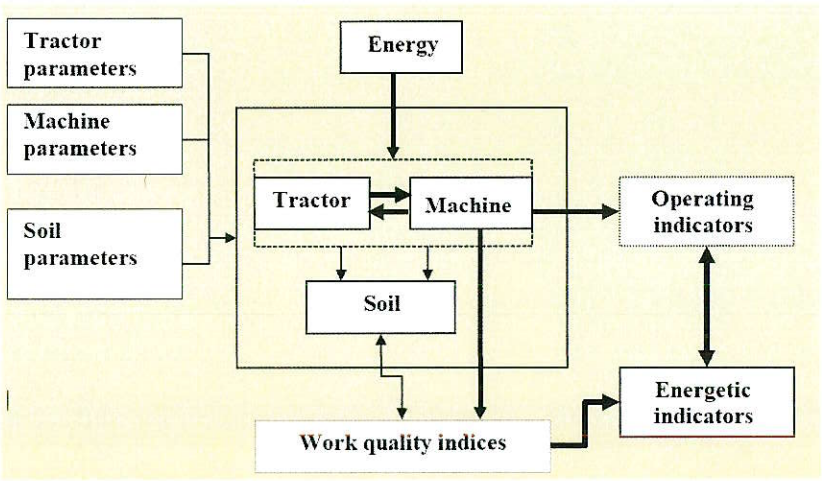


Figure 1. Block diagram of the systemic representation of the tillage process *[14, 17]*

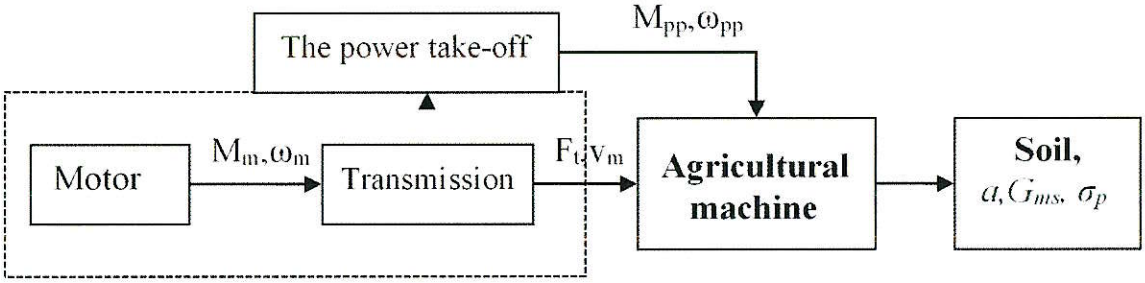


Figure 2. The dynamic model of the agricultural system *[14, 17]*

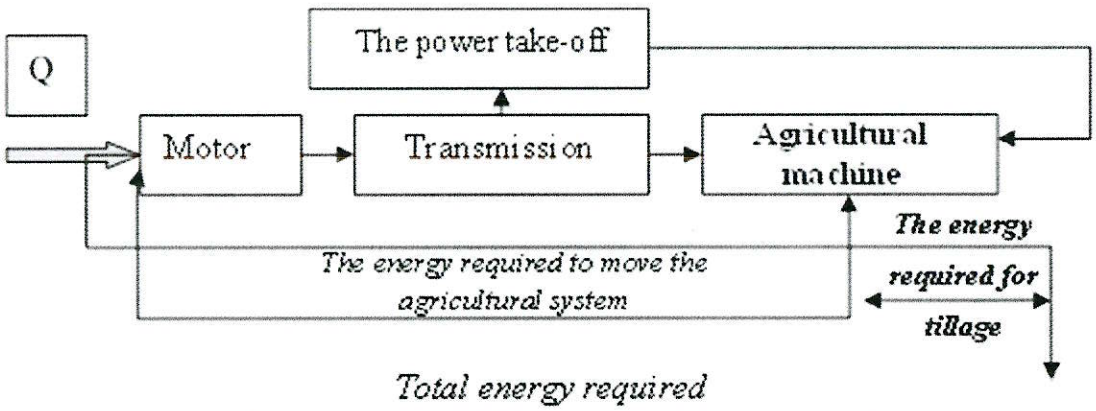


Figure 3. The energetic model of the agricultural system *[14, 17]*

The main objective of this paper is to find and certify a theoretical model and an optimization algorithm using the Newton-Raphson method and a source program written in Python that allows the determination of the optimal operating parameters of a complex agricultural machine for seed-bed preparation.

2. Materials and methods

The complex agricultural machines considered is a vibro-combinator for the seed-bed preparation of the Maschio-Gaspardo company treated by a 250 HP tractor (Fig. 4).



Figure 4. The energetic model of the agricultural system *[23]*

The work proposes to determine the optimal speed and working width for minimum energy consumption, when performing work on a level ground.

To establish the objective function, the energy consumed when traveling under load and when empty is considered, respectively:

$$E_s = P_s T_s \tag{1}$$

and

$$E_g = P_g T_g \tag{2}$$

where:

P_s - is the traction power of the tractor under load;

T_s - is the time corresponding to the movement in the load;

P_g - is the traction power at idle;

T_g - is the time corresponding to the idle travel.

The total energy is given by the relationship:

$$E = P_s T_s + P_g T_g \tag{3}$$

The powers are established according to the traction resistance of the agricultural machines and the travel speed in the respective regimes, as follows:

$$P_s = f_m g_s B_l V_l + f_v g_s B_l V_l^2 + K B_l V_l + K_v B_l V_l^2 \tag{4'}$$

$$P_g = f_m g_s B_l V_g + f_v g_s B_l V_g^2 \tag{4''}$$

where:

g_s- the weight of the work unit of the aggregate [N/m];

V_l- working speed (moving in load) [m/s];

V_g - idling speed [m/s];

f_m- rolling resistance coefficient;

K - the tensile strength of the unit in the width of the agricultural machines [N/m];

K_v - coefficient of increase in traction resistance of agricultural machines due to speed [Ns/m^2];

K_s- coefficient of use of the time of a shift.

The working times in load and idling are given by the relations:

$$T_s = \frac{C \cdot L}{B_l V_l} \quad (5')$$

$$T_g = \frac{C(l_i + m_1 B_l)}{B_l V_g} \quad (5'')$$

where:

C - is the width of the plot [m];
L - the length of the plot [m];
l_i- the length of an empty turn [m];
B_l- aggregate width [m];
m_1 - return parameter.

By making the substitutions in relation (3), we obtain:

$$E = (f_m g_s B_l V_l + f_v g_s B_l V_l^2 + K B_l V_l + K_v B_l V_l^2) \frac{CL}{B_l V_l} + +(f_m g_s B_l V_g + f_v g_s B_l V_g^2) \frac{C(l_i + m_1 B_l)}{B_l V_g}, \ [J] \quad (6)$$

Next, the restriction on work capacity is introduced, namely:

$$\frac{W}{B_l V_l} - K_s = 0 \quad (7)$$

The following optimization problem results from the presented: *to minimize the function from relation (6)*, considering the restriction from relation (7), under the conditions:

$$V_l \geq 0, \ B_l \geq 0 \quad (8)$$

If the two speeds are considered equal, running on load and empty, and the notations are made:

$$x_1 = V_l = V_g, \ x_2 = B_l \quad (9)$$

the need to minimize the function is obtained:

$$E = (f_m g_s CL + K_v CL + f_v g_s C l_i) x_1 + f_v g_s C m_1 x_1 x_2 + f_m g_s C m_1 x_2 + +(f_m g_s CL + KCL + f_v g_s C l_i) = c_1 x_1 + c_2 x_1 x_2 + c_3 x_2 + c_4, \ [J] \quad (10)$$

in conditions:

$$\frac{W}{x_1 x_2} - K_s = 0 \quad (11)$$

$$x_1 \geq 0, \ x_2 \geq 0 \quad (12)$$

To solve the given problem, the method of Lagrange's multipliers is used. In this sense, the auxiliary function is:

$$L(x_1, x_2, \lambda) = E + \lambda(\frac{W}{x_1 x_2} - K_s) \quad (13)$$

From the condition that the partial derivatives of the Lagrange function in relation to the parameters x_1, x_2 and λ are equal to zero, a system of nonlinear equations is obtained:

$$\begin{cases} c_1 + c_2 x_2 - \dfrac{\lambda W}{x_1^2 x_2} = 0 \\ c_2 x_1 + c_3 - \dfrac{\lambda W}{x_1 x_2^2} = 0 \\ \dfrac{W}{x_1 x_2} - K_s = 0 \end{cases} \tag{14}$$

where:

$c_1 = f_m g_s CL + K_v CL + f_v g_s Cl_i$
$c_2 = f_v g_s Cm_1$
$c_3 = f_m g_s Cm_1$

System (14) can be solved directly, obtaining:

$$x_1 = \sqrt{\frac{c_3 W}{c_1 K_s}} \qquad x_2 = \sqrt{\frac{c_1 W}{c_3 K_s}} \tag{15}$$

or applying the Newton Raphson method.
To solve the system (14) by the Newton-Raphson method, the functions of the nonlinear system are first formed, namely:

$$\begin{cases} f_1(x_1, x_2, \lambda) = c_1 + c_2 x_2 - \dfrac{\lambda W}{x_1^2 x_2} \\ f_2(x_1, x_2, \lambda) = c_2 x_1 + c_3 - \dfrac{\lambda W}{x_1 x_2^2} \\ f_3(x_1, x_2, \lambda) = \dfrac{W}{x_1 x_2} - K_s \end{cases} \tag{16}$$

The solution of system (14), obtained by the Newton-Raphson method, is:

$$\begin{Vmatrix} x_1 \\ x_2 \\ x_3 \end{Vmatrix}^{(k+1)} = \begin{Vmatrix} x_1 \\ x_2 \\ x_3 \end{Vmatrix}^{(k)} - A^{-1}(x_1^{(k)}, x_2^{(k)}, \lambda^{(k)}) \begin{Vmatrix} f_1(x_1^{(k)}, x_2^{(k)}, \lambda^{(k)}) \\ f_2(x_1^{(k)}, x_2^{(k)}, \lambda^{(k)}) \\ f_3(x_1^{(k)}, x_2^{(k)}, \lambda^{(k)}) \end{Vmatrix} \tag{17}$$

where:

$$A = \begin{Vmatrix} \dfrac{\partial f_1}{\partial x_1} & \dfrac{\partial f_1}{\partial x_2} & \dfrac{\partial f_1}{\partial \lambda} \\ \dfrac{\partial f_{21}}{\partial x_1} & \dfrac{\partial f_2}{\partial x_2} & \dfrac{\partial f_2}{\partial \lambda} \\ \dfrac{\partial f_3}{\partial x_1} & \dfrac{\partial f_3}{\partial x_2} & \dfrac{\partial f_3}{\partial \lambda} \end{Vmatrix} = \begin{Vmatrix} \dfrac{2\lambda W}{x_1^3 x_2} & c_2 + \dfrac{\lambda W}{x_1^2 x_2^2} & \dfrac{-W}{x_1^2 x_2} \\ c_2 + \dfrac{\lambda W}{x_1^2 x_2^2} & \dfrac{2\lambda W}{x_1 x_2^3} & \dfrac{-W}{x_1 x_2^2} \\ \dfrac{-W}{x_1^2 x_2} & \dfrac{-W}{x_1 x_2^2} & 0 \end{Vmatrix} \tag{18}$$

is the functional matrix of the system of nonlinear equations (14).

After determining the optimal operating parameters, the traction power under load is determined using the first relationship in (4). The effective power of the engine is determined with the relationship:

$$P_e = \frac{P_s}{\eta} \ [W] \tag{19}$$

3. Results

The mathematical system (14) can be solved directly, obtaining the results (15) or by applying the Newton Raphson method and a numerical calculation program.

To determine the optimal operating parameters of a complex aggregate for the preparation of the seedbed under the following working conditions: g_S=800 [N/m], f_m=0.18, f_v=0.01 [s/m], K=3500 [N/m], K_v=100 [Ns/m^2], L=500 [m], C=50 [m], K_s=0.8, l_i=50 [m], m_1=35 , W=11.1 [m^2/s] and η=0.6, the following results are obtained:

V_{opt}=2.7275 [m/s],
B_{opt}=5.0870 [m],
P_S=75.3 [kW],
P_e=125.5 [kW].

4. Discussion

The execution of agricultural works in optimal operating conditions is imperative for the optimal management of energy resources and for obtaining maximum technological performance.

Numerical calculation programs that are based on the Newton-Raphson method can be successfully used to obtain the optimal operating parameters of tillage machines.

5. Conclusions

This study highlights the great advantage of using such an algorithm for calculating the optimal operating parameters of agricultural tillage machines in that it allows the spectacular reduction of the costs necessary to obtain these optimal regimes through experimental trials.

This type of study can be extremely useful both to the manufacturers of tractors and agricultural machines and, at the same time, to those who exploit these technical systems with the aim of reducing fuel consumption and increasing work speed in the conditions of achieving qualitative indices of work as best as possible. Also, such a study can be very useful to students and teachers in higher technical education.

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