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Improving energy efficiency of double-disc coulters using boundary estimation method of seed furrow profile influence

Abstract. The relevance of this study lies in the global demand to increase the energy efficiency of agricultural implements while maintaining high agronomic performance. The purpose of the article was to analytically assess the effect of furrow profile parameters on the operational energy performance of tillage tools, using double-disc openers as an example. The methodology was based on geometric modelling of the working components of the coulters in a Cartesian coordinate system, derivation of parametric equations for furrow contours, and analytical calculation of the furrow cross-sectional area depending on tillage depth, disc diameter, and disc alignment angles. The study demonstrated that the furrow area for discs with a 350 mm diameter increased from 415 mm² to 4106 mm² as the tillage depth rose from 20 mm to 80 mm. With a fixed depth of 50 mm and angles $\alpha = 50^\circ$, $\beta = 20^\circ$, the furrow area varied from 1762 mm² to 1935 mm² as the disc diameter changed from 300 mm to 400 mm. A quadratic approximation formula was proposed to express this dependence.

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The results showed that reducing the tillage depth from 50 mm to 45 mm led to a decrease in furrow area from 1851 mm² to 1277 mm², while increasing the depth to 55 mm resulted in an increase to 2516 mm². The influence of disc inclination angles on the cross-sectional area was also demonstrated: decreasing the angles to $\alpha = 40^\circ$ and $\beta = 15^\circ$ reduced the area to 1522 mm². The proposed approach enabled further configuration optimisation of coulters under real conditions. The methodology presented in this publication makes it possible to determine the most rational configuration of tillage tools for the existing circumstances through appropriate analysis

Keywords: energy efficiency of agricultural machinery; disc tillage tools; mathematical modelling; computer-aided design; computer information technology

INTRODUCTION

In the context of increasing demands for sustainable agriculture and resource-efficient food production, improving the energy performance of tillage implements remains a pressing technical challenge. With the rising cost of fuel, depletion of non-renewable resources, and the need to reduce environmental impacts, modern agricultural machinery must be designed to ensure high productivity with minimal energy input. This necessitates the optimisation of structural and operational parameters of tillage tools, particularly those adapted for conservation agriculture, such as disc-type openers.

V. Damanauskas & A. Janulevičius (2022) noted that due to the existing high environmental requirements and the need to ensure proper energy efficiency, the intensity of tillage is now significantly decreasing. Using the example of a cultivator with elastic tines and a disc harrow, they show that the required soil structure and the desired application of plant residues are realised by fuel consumption, which is determined by the type of tractor, its speed, tillage depth, and soil condition. It is recommended to save energy resources by reducing the depth of cultivation rather than reducing the speed of agricultural units. M. Malasli & A. Çelik (2023) studied the effect of ploughing depth, angles of discs in the horizontal plane and relative to the vertical, emphasising the importance of these parameters for furrow formation, traction forces, and energy consumption. This information shows the relevance of determining the optimal position of tillage tools during their operation. The geometric modelling of furrow profiles of disc tillage tools is the subject of a study by P. Yablonskyi *et al.* (2023; 2025). O. Vorobiov (2024) outlined the principles of analytical and computer reproduction of the structural and operational parameters and characteristics of these tillage tools.

The authors A. Hamid & A. Alsabbagh (2023) studied the effect of shelf types, depths, and cultivation speeds on the obtained agrotechnical characteristics. The prospects of disc tools are associated with the current progressive trends in minimum tillage. Discs, unlike shelf ploughs, significantly reduce energy costs, ensure soil moisture retention, and contribute to its erosion resistance. G. Xu *et al.* (2023) and Z. Zeng *et al.* (2021) performed an experimental study of several disc tillage tools to compare their effectiveness at different furrow profiles, measuring the acting forces and crushing of plant residues. K. Aikins *et al.* (2020) investigated the basic characteristics of coulters, including

soil destruction, low traction resistance, and accurate seed and fertiliser placement. D. Parihar *et al.* (2023) compared openers in terms of furrow formation, energy consumption and sowing performance. The publication of F. Chandio *et al.* (2020) is devoted to the mathematical prediction of the forces acting on the discs and the resulting soil deformations depending on the speed and depth of cultivation. O. Ranta *et al.* (2021) note that there is a growing interest in farming, which involves sowing into untreated soil by forming the necessary furrows. This preserves moisture in the soil and prevents soil erosion. Several types of discs and sowing speeds have been studied to define rational agronomic regimes. It is emphasised that more attention should be paid to the design of soil-adapted coulters, as well as the possibility of their real-time adjustment to improve the quality of work performed. In the work of S. Nikolaenko *et al.* (2021) indicated that the training of mechanical engineers, technologists and designers in agricultural higher education institutions requires innovative integrated approaches that provide relevant in-depth theoretical knowledge, sufficient practical skills, and an appropriate level of proficiency in modern computer information technologies. In this regard, the information presented in this publication will also be quite useful. Thus, the analysis of existing approaches shows that further improvement of disc tillage tools is quite relevant. This is due to the need to solve urgent problems of food security with minimal energy costs.

This article is aimed at solving some of the problems of this topic. In particular, this concerns optimisation of the operation of double-disc openers by selecting rational disc diameters, their installation angles, tillage depths, travel speeds, etc. The scientific novelty of the study lies in the proposed method of boundary estimates of the influence of the furrow profile on the operational energy characteristics of tillage tools, presented on the example of double-disc coulters.

MATERIALS AND METHODS

For soil cultivation, their main components (Fig. 1) were the riser 1, axle 2 and flat discs 3. Such components as seed pipes, wrappers, etc. that were not essential for determining the required furrow were not considered in the cited articles. This also applied to additional structural elements that can remove the ridge formed between the discs and the soil from the furrow walls. These tasks should be the subject of further scientific research.

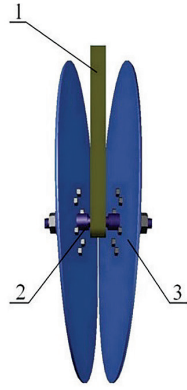


Figure 1. Main tillage components of the double disc coulters

Note: 1 – riser, 2 – axle, 3 – disc with hub and rolling element

Source: developed by the authors

The image in Figure 1 corresponds to the view in the direction of travel of the opener. The round flat discs are placed symmetrically with respect to the longitudinal vertical plane of symmetry of the implement. They are positioned in the Cartesian coordinate system $Oxyz$ with the origin O at the point of intersection of the disc axes, the x -axis opposite to the direction of the coulters movement, the horizontal plane Oxy and the vertical axis z . The discs are rotated by an angle of α relative to the x -axis in the horizontal plane and deviated by an angle β from the vertical. During operation, they rotate around their axes, cut, spread and compact the soil to form a furrow. Its profile, i.e. cross section, depends on the diameter D of the discs, the required processing depth a , and the angles α and β . The latter also determine the location of the convergence point S , which corresponds to the minimum distance between the discs (Fig. 2). To simplify the analytical calculations, the original $Oxyz$ coordinate system was moved to the centre of the left disc by parallel transfer.

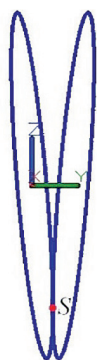


Figure 2. Point S of disc convergence

Source: developed by the authors

According to O. Vorobiov (2024), the parametric equations of the contours are as follows:

for the left (first) disc:

$$\begin{aligned} x(u) &= \frac{D}{2}(\cos\alpha \cos(u) + \sin\alpha \sin\beta \sin(u)), \\ y(u) &= \frac{D}{2}(\cos\alpha \sin\beta \sin(u) - \sin\alpha \cos(u)), \quad z(u) = -\frac{D}{2}\cos\beta \sin(u); \end{aligned} \quad (1)$$

for the right (second) disc:

$$\begin{aligned} x(u) &= \frac{D}{2}(\cos\alpha \cos(u) + \sin\alpha \sin\beta \sin(u)), \\ y(u) &= 2y_s + \frac{D}{2}(\sin\alpha \cos(u) - \cos\alpha \sin\beta \sin(u)), \\ z(u) &= -\frac{D}{2}\cos\beta \sin(u), \end{aligned} \quad (2)$$

where D is the diameter of the discs; $\alpha \in (0^\circ, 90^\circ)$, $\beta \in (0^\circ, 90^\circ)$ are the intervals of change in the angles α and β ; y_s is the ordinate of the point S of the discs' convergence; $u \in [0^\circ, 360^\circ]$ is a parameter corresponding to the angle in the plane of the disc with the vertex in its centre, the base side directed to the rear point of the horizontal diameter (Fig. 2), and is counted counterclockwise, looking against the direction of the y -axis. Conforming to O. Vorobiov (2024) shows that the vanishing point S corresponds to the parameter:

$$u_s = \arctg(-\text{ctg} \cdot \sin\beta) + 180^\circ. \quad (3)$$

By substituting the value from expression (3) into expression (1), the required value of y_s for the ordinate y in ratio (2) is obtained. The furrow pattern of a double disc coulters is illustrated in Figure 3, where h is the distance from the centre of the discs to the ground.

The applications of formulas (1) and (2) show that for the lowest positions of the first and second discs the parameter $u = 90^\circ$. Then the distance between these points (Fig. 3):

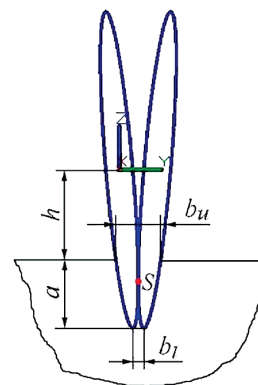


Figure 3. Furrow profile depending on the tillage depth a

Note: h – distance from the centre of the discs to the ground; a – tillage depth; S – point of minimum distance between discs; b_l – distance between the lowest points of the discs; b_u – width of the top of the furrow profile

Source: developed by the authors

$$\begin{aligned} b_l &= 2y_s + \frac{D}{2}(\sin\alpha \cos(90^\circ) - \cos\alpha \sin\beta \sin(90^\circ)) - \\ &- \frac{D}{2}(\cos\alpha \sin\beta \sin(90^\circ) - \sin\alpha \cos(90^\circ)) = 2y_s - D \cos\alpha \sin\beta. \end{aligned} \quad (4)$$

In practice, considering the gap d_s between the discs at the point of their convergence, the following expression is obtained:

$$b_l = 2y_s - D \cos \alpha \sin \beta + d_s. \quad (5)$$

The study by O. Vorobiov (2024) shows that the initial upper position of the furrow profile is determined by the parameter:

$$u_u = \arcsin\left(1 - \frac{2a}{D \cos \beta}\right). \quad (6)$$

The maximum processing depth a_{\max} of the disc at twothirds of its radius corresponds to the gap:

$$u \in [u_{\min}, u_{\max}] = [19.5^\circ, 160.5^\circ], \quad (7)$$

For a specific furrow:

$$u \in [u_u, 180^\circ - u_u], \quad (8)$$

where:

$$u_u \in [u_{\min}, 90^\circ]. \quad (9)$$

As can be seen from Figure 3 and expressions (1) and (2), the width b_u of the top of the furrow profile is equal to:

$$\begin{aligned} b_u &= 2y_s + \frac{D}{2}(\sin \alpha \cos(u_u) - \cos \alpha \sin \beta \sin(u_u)) - \\ &\quad - \frac{D}{2}(\cos \alpha \sin \beta \sin(u_u) - \sin \alpha \cos(u_u)) = \\ &= 2y_s + D(\sin \alpha \cos(u_u) - \cos \alpha \sin \beta \sin(u_u)). \end{aligned} \quad (10)$$

Considering the minimum distance d_s between the discs at the point of their convergence, the following expression is obtained:

$$b_u = 2y_s + D(\sin \alpha \cos(u_u) - \cos \alpha \sin \beta \sin(u_u)) + d_s. \quad (11)$$

Thus, relations (1)-(11) for the double disc coulters under consideration make it possible to analytically determine the theoretical profile of the furrow they form. These data are necessary, but not sufficient for rational management of the energy efficiency of the studied agricultural implements. The useful work performed by a tillage implement W_{ti} under stable operating conditions (or proper average values over a certain period of time) is determined by the formula:

$$W_{ti} = F_{ti} \cdot L_{ti}, \quad (12)$$

where F_{ti} is the force of resistance of the soil and the implement; L_{ti} is the distance travelled.

In dependence (12), it is assumed that the tillage tools are moving in a straight line with a constant speed. Therefore, the total traction force applied to them acts along the specified trajectory, is equal to the resistance force of the soil and the implement, and has the opposite direction to it. The term "total traction force" refers to the total effect of traction. For example, driving downhill reduces the actual traction force of the tractor, while driving uphill increases it, and so on. Also, the "soil and implement resistance force" includes both the direct resistance of the deformed soil and additional components related, in particular, to the features of the structure used, its operational condition, etc. It is once again emphasised that the method of boundary estimation of the influence of the furrow profile on the operational energy characteristics of tillage tools, as

proposed in this study, is based on parameters and properties averaged over a specified time interval T_{ti} .

By dividing both left and right sides of expression (12) by the interval T_{ti} under study, the following result is obtained:

$$P_{ti} = \frac{W_{ti}}{T_{ti}} = F_{ti} \cdot \frac{L_{ti}}{T_{ti}} = F_{ti} \cdot V_{ti} \quad (13)$$

where P_{ti} is the required power; V_{ti} is the operating speed of the implement. The components F_{ti} and V_{ti} of formula (13) are functions of many different factors. For example:

$$F_{ti} = f_{ti}(SP, TI, PP, \dots), \quad (14)$$

where soil properties:

$$SP = (MC, SST, SM, PC, HM, SA, \dots); \quad (15)$$

its mechanical composition:

$$MC = (SS, CS, LM, BS, \dots), \quad (16)$$

where *SS* – sandy soils, *CS* – clay soils, *LM* – loams, *BS* – black soil; soil structure:

$$SST = (SLST, LMST, LSST, \dots), \quad (17)$$

where *SLST* – solid, *LMST* – lumpy, *LSST* – loose; *SM* – soil moisture, *PC* – previous crops, *HM* – humus, *SA* – soil aeration; tillage implements:

$$TI = (MLB, DSC, CHL, \dots), \quad (18)$$

where *MLB* – moldboard, *DSC* – disc, *CHL* – chisel; processing parameters:

$$PP = (a, V_{ti}, A, \dots), \quad (19)$$

where a is tillage depth, V_{ti} is the speed of the tillage tool, and A is the area of the furrow profile. The functional dependence for the speed of the implement as a component of the tractor unit can be represented as:

$$V_{ti} = \frac{P_{tr} \cdot k_{pttr}}{n_{ti} \cdot F_{ti}}, \quad (20)$$

where P_{tr} is the nominal power of the tractor; power transmission ratio of the tractor to agricultural implements:

$$0 < k_{pttr} < 1, \quad (21)$$

n_{ti} is Thus, operational energy performance, see expressions (12)-(21), depends on many parameters and characteristics (see for example Ya. Pavlova & D. Litvinov (2024)). Therefore, it is quite problematic to accurately reflect them with one universal analytical mathematical apparatus. It is proposed to solve this complex problem by dividing the latter into several simpler ones.

An increase in the operational speed (20) of agricultural implements increases the productivity of agricultural processes. The analysis of this formula shows that this is facilitated by an increase in tractor power and the coefficient of its transmission to tillage tools. However, the former requires adequate energy, financial and other costs. The second approach is more economical but has certain limitations (21). An increase in the number of aggregated

implements n_{ti} slows down their speed but increases the area worked. Therefore, this value requires the definition of an optimal value. The most appropriate is to reduce the force F_{ti} of soil and tool resistance. This article is devoted to these issues.

The main idea is to use the experience gained in cultivating certain agricultural lands. This applies to both small and large farms. Each of them cultivates fields with certain soil properties (15), their mechanical composition (16), and structure (17). There is also statistical information available, at the required time periods, on soil moisture, humus, aeration, previous crops, etc. There is data on the tillage tools used, the appropriate tillage parameters (19), the tractor fleet used, and its technical characteristics. There are also corresponding farming results. The question is whether the latter can be improved, for example, in terms of increased yields, labour productivity, reduced energy and financial costs, etc.

The above studies, approaches, mathematical apparatus and considerations served as the basis for determining the methodology for conducting scientific research aimed at improving the energy efficiency of tillage tools on the example of double-disc coulters. The proposed methods consist in establishing analytical dependencies between certain parameters of the design of agricultural implements (for the studied openers, these are the diameter of the discs D , the minimum distance d_s between them, the installation angles α, β) and the resulting operational characteristics associated with energy consumption (in this case, these are the depth of cultivation a , the furrow profile and its area A).

Their increase or decrease enables the estimation of the relative increase or decrease in fuel consumption for the implementation of the technological process. The following general approach of marginal estimates, illustrated on the example of double disc coulters, can be extended to other tillage tools and other, not only agricultural, equipment. However, this is the subject of further research. The proposed methodology for some aspects of improving the energy efficiency of agricultural tillage tools, presented on the example of double-disc openers, is as follows. The accumulated cultivation experience is selected as the starting point for the optimisation. The direction of the desired improvements is determined based on analytically determined limit estimates of the influence of the furrow profile on the operational energy characteristics of tillage tools.

$$\begin{aligned}
 y'(u) &= \frac{D}{2} (\cos \alpha \sin \beta \cos(u) + \sin \alpha \sin(u)), \\
 \int_{u_u}^{u_s} z(u) y'(u) du &= \int_{u_u}^{u_s} \frac{D}{2} \cos \beta (1 - \sin(u)) \cdot \frac{D}{2} (\cos \alpha \sin \beta \cos(u) + \sin \alpha \sin(u)) du = \\
 &= \frac{D^2}{4} \cos \beta (\cos \alpha \sin \beta \int_{u_u}^{u_s} \cos(u) du + \sin \alpha \int_{u_u}^{u_s} \sin(u) du - \\
 &\quad - \cos \alpha \sin \beta \int_{u_u}^{u_s} \sin(u) \cos(u) du - \sin \alpha \int_{u_u}^{u_s} \sin^2(u) du) = \\
 &= \frac{D^2}{4} \cos \beta (\cos \alpha \sin \beta \sin(u) \Big|_{u_u}^{u_s} - \sin \alpha \cos(u) \Big|_{u_u}^{u_s} - \\
 &\quad - \frac{\cos \alpha \sin \beta \sin^2(u)}{2} \Big|_{u_u}^{u_s} - \sin \alpha (\frac{u}{2} - \frac{\sin(2u)}{4}) \Big|_{u_u}^{u_s}), \tag{25}
 \end{aligned}$$

RESULTS AND DISCUSSION

As can be seen from formulas (13)-(21), for certain existing soil properties (mechanical composition, structure, moisture, previous crops, etc.), the tools used (in this case, double-disc coulters), cultivation parameters (in the form of the required depth, operating speed, furrow profile, furrow area) and the available technical park, certain agricultural results are achieved due to specific energy inputs (tractor power).

Increasing productivity, i.e. V_{ti} and n_{ti} , by increasing the power P_{tr} of tractors, see dependence (20), is obvious, but it does not improve energy efficiency. Increasing the coefficient k_{ptr} is important, but does not correspond to the chosen topic of this research. An effective way is to reduce the resistance force F_{ti} of the soil and the implement. Then, with other operating parameters remaining constant, labour productivity increases due to an increase in V_{ti} or energy costs are reduced by reducing the required power P_{tr} .

Based on expressions (1)-(11) and Figure 3, an analytical determination of the area A of the furrow profile formed by a double disc coulters is carried out, as this parameter is particularly significant for the resistance force F_{ti} acting between the soil and the tool. To do this, move the $Oxyz$ coordinate system vertically downwards so that the Oxy plane coincides with the level of the furrow bottom. Then the applications in relations (1) and (2) will be equal to:

$$z(u) = -\frac{D}{2} \cos \beta \sin(u) + \frac{D}{2} \cos \beta = \frac{D}{2} \cos \beta (1 - \sin(u)). \tag{22}$$

Further, based on the integral for calculating the area of the curved trapezoid bounded by the parametric curve and the symmetry of the furrow profile relative to the vertical axis passing through the point S of the discs' convergence, the following is obtained:

$$A = 2 \cdot ((y_s - y_u + \frac{d_s}{2}) \cdot a - \int_{u_u}^{u_s} z(u) y'(u) du), \tag{23}$$

where $y(u)$ is the ordinate of the first disc, $z(u)$ is determined according to formula (22). The components of dependence (23) are as follows:

$$\begin{aligned}
 y_s &= y(u_s) = \frac{D}{2} (\cos \alpha \sin \beta \sin(u_s) - \sin \alpha \cos(u_s)), \\
 y_u &= y(u_u) = \frac{D}{2} (\cos \alpha \sin \beta \sin(u_u) - \sin \alpha \cos(u_u)), \tag{24}
 \end{aligned}$$

where $u_s = \arctg(-ctg \alpha \cdot \sin \beta) + 180^\circ$, $u_u = \arcsin(1 - 2a / (D \cdot \cos \beta))$;

where angles α, β , parameters u_s, u_u are measured in radians. Expressions (23) and (25) make possible to determine the area A of the furrow profile of a two-disc coultter with diameters D of the discs and the minimum distance d_s between them, their installation angles α and β . To illustrate the proposed approach, the furrow profile defined by the design parameters of the opener in O. Vorobiov (2024) is used as the initial condition:

$$D = 350 \text{ mm}, \alpha = 5^\circ, \beta = 20^\circ. \quad (26)$$

In addition to the values specified in expression (26), it is necessary to consider a zero minimum distance between the discs and working range of tillage depths.

$$a \in [20 \text{ mm}, 80 \text{ mm}]. \quad (27)$$

The proper furrow profile is illustrated in Figure 4. The second image shows the ridge that forms at the bottom of the furrow. Its width at heights greater than one millimetre is mostly less than a millimetre. In other words, in practice, the shape of this ridge would be described by an approximately equilateral trapezoid with a height of 1 to 1.5 mm and a lower and upper base of 3 mm and 1 mm, respectively. These geometric parameters are acceptable. These aspects will not be considered in further detail.

Table 1 contains the results of calculations based on expressions (23)-(27) of the area A of the furrow profile for $D = 350 \text{ mm}, \alpha = 5^\circ, \beta = 20^\circ$ depending on the depth a of tillage.

Table 1. Variation of furrow profile area A for $D = 350 \text{ mm}, \alpha = 5^\circ, \beta = 20^\circ$

Tillage depth a , mm	20	30	40	50	60	70	80
Furrow profile area A , mm ²	415	796	1,277	1,851	2,516	3,268	4,106

Source: compiled by the authors

The corresponding quadratic approximation formula is:

$$A(a) = k_2 a^2 + k_1 a + k_0, \quad (28)$$

where $k_2 = 91/200, k_1 = 1,129/70, k_0 = -1,305/14$. The corresponding graph is shown in Figure 5.

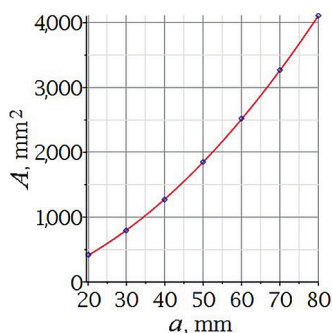


Figure 5. Visualisation of expression (28)

Source: developed by the authors

It is obvious that the first depth saves energy and financial costs, but can lead to a deterioration in agronomic performance. In the second case, the opposite is true. The assessment of agrotechnical factors, unlike energy factors,

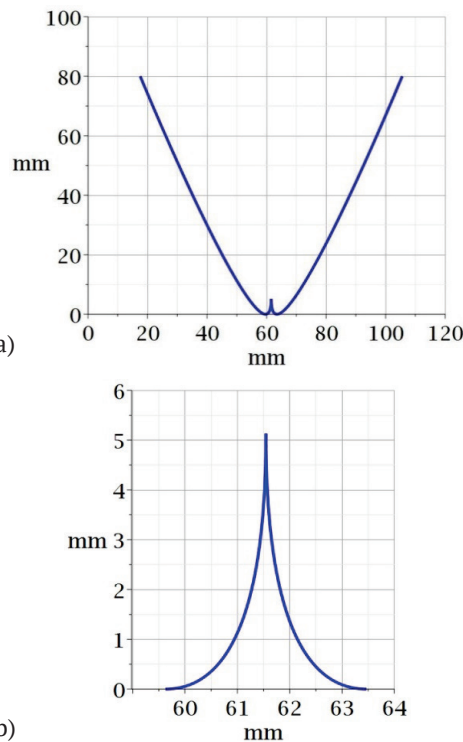


Figure 4. Furrow profile for $D = 350 \text{ mm}, \alpha = 5^\circ, \beta = 20^\circ$

Note: a) general view; b) crest

Source: developed by the authors

is not the subject of this publication. Consideration is given to a case where the current tillage depth is $a_0 = 50 \text{ mm}$, and the suitability of two alternative depths, $a_1 = 45 \text{ mm}$ and $a_2 = 55 \text{ mm}$, is evaluated. To determine the most appropriate option, the following procedure is applied. It is obvious that the first depth saves energy and financial costs, but can lead to a deterioration in agronomic performance. In the second case, the opposite is true. The assessment of agrotechnical factors, unlike energy factors, is not the subject of this publication. In accordance with the proposed approach, expression (28) provides a means to determine the limits of variation in energy costs, whether increasing or decreasing.

$$A(a_0) = 1,851 \text{ mm}^2, A(a_1) = 1,554 \text{ mm}^2, A(a_2) = 2,170 \text{ mm}^2. \quad (29)$$

Using the data provided in expression (29), the following boundary estimates of R (rating) are obtained, reflecting the impact of changes in the furrow profile on the operational energy characteristics of the double disc coultter under consideration.

$$R_1 = \frac{A(a_0)}{A(a_1)} = \frac{1,851 \text{ mm}^2}{1,554 \text{ mm}^2} \approx 1.19, \\ R_2 = \frac{A(a_0)}{A(a_2)} = \frac{1,851 \text{ mm}^2}{2,170 \text{ mm}^2} \approx 0.85. \quad (30)$$

The values of (30) show that the savings Sav (saving) of energy resources and their overspending Ovs (overspending) are approximately:

$$\begin{aligned} Sav &= (1 - 1/R_1) \cdot 100\% \approx 16\%, \\ Ovs &= (1/R_2 - 1) \cdot 100\% \approx 17\%. \end{aligned} \quad (31)$$

Thus, if the savings (31) of energy resources in financial terms cover the possible losses from the deterioration of agronomic performance, then the analysed tillage depth $a_1 = 45$ mm is appropriate, otherwise – not. By analogy, if

the additional costs (31) are less than the gains from improved agronomic performance, then the new tillage depth $a_2 = 55$ mm is appropriate, otherwise it is not. In the following, the financial efficiency of the proposed changes in the furrow profile is assessed in a similar way and is therefore no longer emphasised. The mathematical apparatus presented above makes it possible to assess the influence of disc diameters D on the energy efficiency of the coulter. It is assumed that the values presented in Table 2 need to be calculated.

Table 2. Variation of furrow profile area A for $a = 50$ mm, $\alpha = 5^\circ$, $\beta = 20^\circ$

Diameter D of discs, mm	300	320	350	380	400
Furrow profile area A , mm ²	1762	1,798	1,851	1,902	1,935

Source: compiled by the authors

The proper expression of the quadratic approximation is:

$$A(D) = k_2 D^2 + k_1 D + k_0, \quad (32)$$

where $k_2 = 0.000981$, $k_1 = 2.41766$, $k_0 = 1,124.9387$. The corresponding graph is shown in Figure 6.

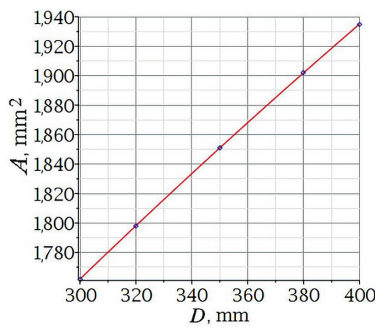


Figure 6. Visualisation of dependency (32)

Source: developed by the authors

Figure 7 shows the variation of the furrow ridge for two disc diameters D .

Suppose that from the point of view of agrotechnical requirements, the ridge of Figure 7b is too large, and the furrow variant of Figure 7a is acceptable. In the latter case, the energy savings will be:

$$\begin{aligned} Sav &= \left(1 - \frac{A(D=320 \text{ mm})}{A(D=350 \text{ mm})}\right) \cdot 100\% = \\ &= \left(1 - \frac{1,798 \text{ mm}^2}{1,851 \text{ mm}^2}\right) \cdot 100\% \approx 2.9\%. \end{aligned} \quad (33)$$

The formula (32) allows processing arbitrary disc diameters from the range:

$$D \in [300 \text{ mm}, 400 \text{ mm}]. \quad (34)$$

By comparing the respective values of expressions (31) and (33), it is concluded that the depth a of tillage has a significantly greater impact on energy saving than the diameters D of the discs used. The integrated effect of the considered operational and design parameters is possible. For

instance, given $a = 45$ mm, $\alpha = 5^\circ$, $\beta = 20^\circ$, and $D = 320$ mm, the following result is obtained:

$$\begin{aligned} Sav &= \left(1 - \frac{A(a=45 \text{ mm}, \alpha=5^\circ, \beta=20^\circ, D=320 \text{ mm})}{A(a=50 \text{ mm}, \alpha=5^\circ, \beta=20^\circ, D=350 \text{ mm})}\right) \cdot 100\% = \\ &= \left(1 - \frac{1,507 \text{ mm}^2}{1,851 \text{ mm}^2}\right) \cdot 100\% \approx 18.6\%. \end{aligned} \quad (35)$$

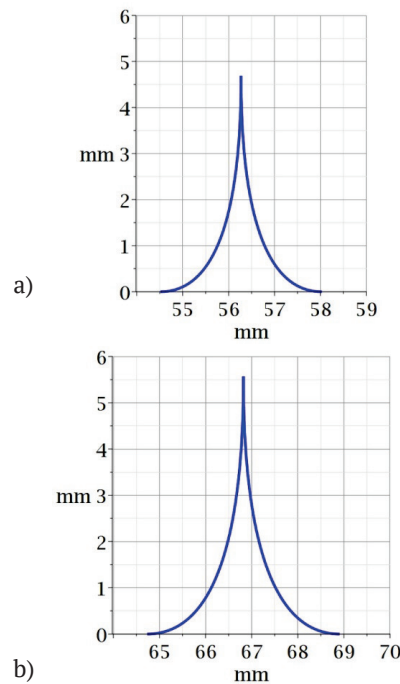


Figure 7. Furrow ridges for $a = 50$ mm, $\alpha = 5^\circ$, $\beta = 20^\circ$

Note: a) $D = 320$ mm; b) $D = 380$ mm

Source: developed by the authors

The value (35) describes the relative estimate of the energy reduction. A proper furrow profile is shown in Figure 8.

The dependencies (23) and (25), for example, for $\alpha = 5^\circ$, $\beta = 20^\circ$ and the intervals (27) and (34), can be visualised using Table 3. The previously calculated values by expressions (28) and (32) are highlighted in blue.

Figure 9 illustrates the calculated results.

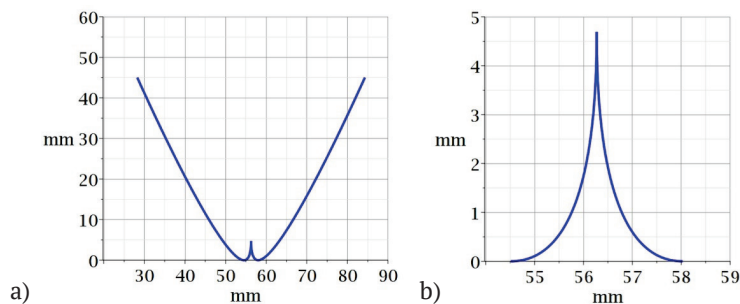


Figure 8. Furrow profile for $D=320$ mm, $\alpha=5^\circ$, $\beta=20^\circ$, $a=45$ mm

Note: a) general view; b) crest

Source: developed by the authors

Table 3. Furrow profile area A , mm²

Tillage depth a , mm	Diameters of discs				
	$D=300$ mm	$D=320$ mm	$D=350$ mm	$D=380$ mm	$D=400$ mm
20	390	400	415	430	440
30	753	771	796	822	838
40	1,212	1,238	1,277	1,314	1,338
50	1,762	1,798	1,851	1,902	1,935
60	2,401	2,448	2,516	2,591	2,624
70	3,126	3,184	3,268	3,350	3,402
80	3,933	4,004	4,106	4,205	4,269

Source: compiled by the authors

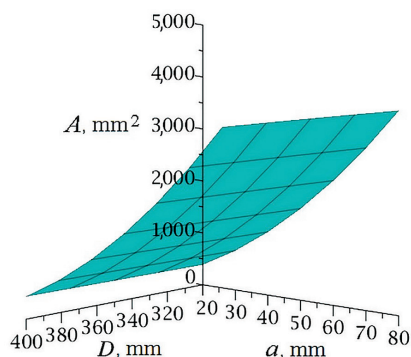


Figure 9. Dependence of the area A of the furrow profile for $\alpha=5^\circ$, $\beta=20^\circ$

Source: developed by the authors

The proper formulas are as follows:

$$A(D, a) = k_2(D) \cdot a^2 + k_1(D) \cdot a + k_0(D), \quad (36)$$

where $k_2(D) = -13/2046240000 \cdot D^2 + 16361/70992000 \cdot D + 7254577/19325600$, $k_1(D) = -6803/204624000 \cdot D^2 + 9618/1987776 \cdot D + 6261669/1932560$, $k_0(D) = 281/426300 \cdot D^2 - 231883/414120 \cdot D + 2184507/96628$. Figure 10 shows, for example, the effect of changing the angles α and β of the discs on the resulting furrow profile.

In the first and second cases, the furrow profile area is respectively:

$$A_1 = 1,330 \text{ mm}^2, A_2 = 1,160 \text{ mm}^2. \quad (37)$$

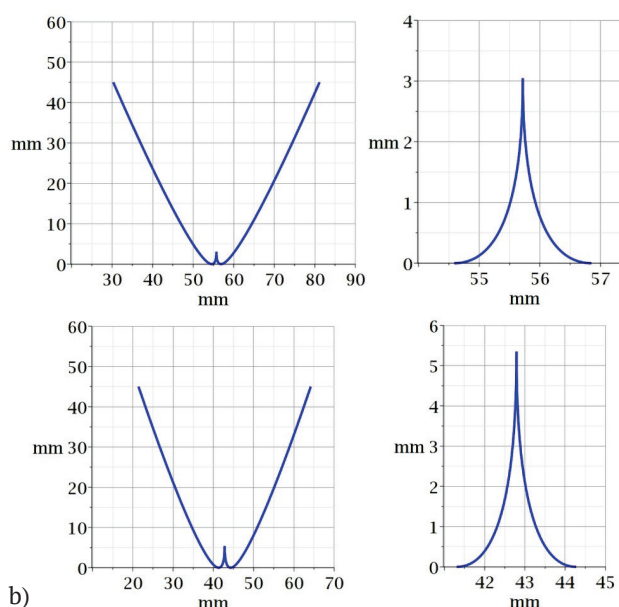


Figure 10. Furrow profiles and ridges for $D=320$ mm, $a=45$ mm

Note: a) $\alpha=4^\circ$, $\beta=20^\circ$; b) $\alpha=4^\circ$, $\beta=15^\circ$

Source: developed by the authors

As evidenced by the values of (37), reducing the angles α and β significantly affects the decrease in the furrow profile area. However, it is necessary to take into account,

in addition to agrotechnical indicators, the possibility of constructive implementation of the analysed geometric

parameters. Thus, compared to the initial state, the reduction in energy resources can be as follows:

$$Sav_1 = \left(1 - \frac{A(\alpha=45 \text{ mm}, \alpha=4^\circ, \beta=20^\circ, D=320 \text{ mm})}{A(\alpha=50 \text{ mm}, \alpha=5^\circ, \beta=20^\circ, D=350 \text{ mm})}\right) \cdot 100\% = \left(1 - \frac{1,330 \text{ mm}^2}{1,851 \text{ mm}^2}\right) \cdot 100\% \approx 28\%,$$

$$Sav_2 = \left(1 - \frac{A(\alpha=45 \text{ mm}, \alpha=4^\circ, \beta=15^\circ, D=320 \text{ mm})}{A(\alpha=50 \text{ mm}, \alpha=5^\circ, \beta=20^\circ, D=350 \text{ mm})}\right) \cdot 100\% = \left(1 - \frac{1,160 \text{ mm}^2}{1,851 \text{ mm}^2}\right) \cdot 100\% \approx 37\%. \quad (38)$$

The values of (38) show that energy consumption varies widely for different crops grown. However, the issue of ensuring flexible adaptation of coulters to specific operating conditions is not clear. It is understood that these actions should have positive generalised effects, and not lead to an increase in the cost of adjusting the openers. It should also be noted that the methods described above allow for the calculation, for the angles α and β , of the dependencies of the form (36) reflecting their influence on the size of the area A of the furrow profile and, accordingly, on energy efficiency.

To compare the results obtained with similar studies by other authors, additional study of the available literature on the selected topic was conducted, see Figure 11. Common and distinctive features of the approaches and methods employed, the nature of the aspects investigated, as well as the theoretical and practical significance of the results, have been identified. Thus, the publication of M. Sadek *et al.* (2021) is devoted to the prediction of traction force during high-speed (12 km/h and more) tillage with disc tools. These parameters are important dynamic components of these energy processes. As mathematical

and computer tools, the discrete element method was used, which is designed to analyse the movement of a large number of specific particles that interact with each other as a result of external influences on them. It is shown that, compared to real values, the model error ranges from 8% to 14%. To eliminate this defect, the model was adapted and an accuracy of 1% was achieved. After that, the influence of the angles of deviation of the disc from the vertical and horizontal planes, its diameter, depth, and tillage speed on the traction force was evaluated. The advantage of the considered methodology is the sufficient accuracy of the description of these parameters in limited intervals of their change for a certain state of the analysed soil. It should be noted that the results obtained will be satisfactory in practice only if the existing conditions coincide with the studied ones, which is generally unlikely. The approach proposed by the authors of this article, in order to optimise the operational energy characteristics of agricultural implements, is based on the existing circumstances of the latter's functioning. This ensures the necessary adequacy of the applied theoretical model to the specific conditions of practice (Pavlova & Litvinov, 2024).

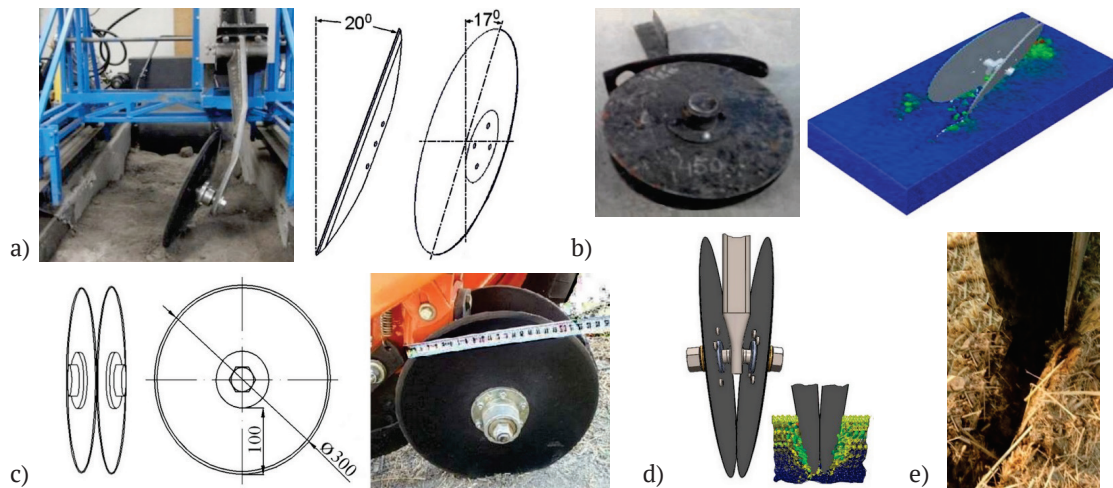


Figure 11. Graphic illustrations of the results of works on the selected topic by other authors

Note: a) M. Sadek *et al.* (2021); b) F. Ahmad *et al.* (2020); c) D. Karayel *et al.* (2024); d) A. Sugirbay *et al.* (2023); e) B. Rosu *et al.* (2024)

Source: developed by the authors

F. Ahmad *et al.* (2020) used the discrete element method to study several different designs of disc coulters. The emphasis is placed on various mechanical properties of the soil, such as its density, shear modulus, Poisson's ratio, friction coefficients, etc. The error between the calculated and actual values of the required traction force, depending

on the speed of the double-disc coulters, ranges from 1% to 21%. This information to some extent complements the information presented in the previous paragraph. But, unfortunately, in reality, there are a huge number of such possible combinations of parameters and characteristics. Therefore, the probability of the existence of the options

considered in advance in specific business circumstances is quite small. The described methodology is of practical value for direct application in the relevant agricultural fields, as indicated in the title of this publication. D. Karayel *et al.* (2024) studied the issue of ensuring the required productivity of a seeder without plowing by finding the right balance between the design of the coulter and the available soil coverage with plant residues. Corn sowing after wheat harvest was analysed. Plain and ripple coulters were tested as variant components of the seeder. Recommendations for their practical use were formulated. This work demonstrates the relevance of analysing, in addition to conventional discs, also their design modifications.

A double-disc coulter for a no-till seeder with simultaneous fertiliser and seed application is presented by A. Sugirbay *et al.* (2023). The proposed design is based on an improvement of the conventional coulter shown in Figure 11d. In the furrow, granular fertilisers are placed 2 cm deeper than the level of wheat seeds. Comparative experiments of the basic and developed double-disc coulters were conducted in a soil bunker. Horizontal and vertical forces were determined, and the accuracy of fertiliser and seed placement was analysed. The behaviour of soil particles interacting with the coulter was simulated using the discrete element method. The agreement between the modelling results and physical experiments is satisfactory. Based on the information presented in this publication, it can be concluded that the design of multifunctional implements based on double-disc openers and the proper use of computer software implementations of the discrete element method are promising.

B. Rosu *et al.* (2024) believed that agricultural specialists should pay more attention to the capabilities of disc tools, their adaptation to specific operating conditions by adjusting the angles of the discs, speed, etc. in order to increase the accuracy of sowing, especially for no-till cultivation, see Figure 11e. This emphasises the aspect of changes in parameters such as the size and weight of the coulter discs due to soil contact. For the studied range of openers, it was found that, on average, the discs thinned by about 0.25 mm per 100 hectares sown, and their diameter decreased by 0.17-0.35% for the sown area from 80 to 380 hectares. It is noted that new research is needed to generalise the results obtained for other types of seeders, as well as to determine the dependence of the above values on various soil properties. Thus, the analysed publication from the standpoint of a systematic approach properly complements the above methodology for the creation and use of double-disc coulters. N. Kumar *et al.* (2021) examined the shredding of plant residues using various disc coulters by different disc coulters (plain, notch, curved teeth, cutter bar and star wheel).

Thus, the considered literary sources were analysed similar design and operational parameters of openers (disc diameters, their installation angles, depth of cultivation), but for certain working speeds and tractors, used soils, their condition, etc. As can be seen from formulas (12)-(21), the

number of possible combinatorial variants of the above factors is almost infinite. In other words, the research carried out makes practical sense only if the existing specific conditions of agricultural production coincide with the analysed ones quite accurately. In cases where these conditions differ, there is a need for a more flexible methodological approach. To some extent, the approach proposed in this article is aimed at resolving this complex issue. Its basic idea is, so to speak, to start from the existing economic circumstances and identify promising areas for their improvement. In particular, this applies to the increase in energy efficiency of tillage tools considered on the example of double-disc coulters without deterioration of the agro-technical indicators obtained.

The conducted study confirmed the feasibility and practical value of a methodological approach based on marginal estimates of the impact of the furrow profile on the energy characteristics of tillage tools. Using the example of double-disc openers, the analytical relationships between design parameters and energy performance indicators were derived and validated, allowing for justified optimisation decisions. The obtained results demonstrate that even minor adjustments in disc diameter, installation angles, or tillage depth may lead to significant variations in energy consumption, offering a potential reserve for resource savings.

CONCLUSIONS

Improving the energy efficiency of tillage implements, in particular seed sowing machines, while ensuring a high level of agrotechnical and environmental requirements is an urgent scientific and applied problem. In this direction, the double-disc coulters of modern seeders are quite promising, and at the same time, the most used in production. The article analytically evaluates the influence of the parameters of the seeding furrow profile on the energy performance of double-disc openers. By geometric modelling of the working surfaces of the coulter, the parametric equations of the contours of the seed furrow in the Cartesian coordinate system were derived and the analytical calculation of its cross-sectional area was performed depending on the depth of cultivation, disc diameter, and disc alignment angles. Using a quadratic approximation formula, it was found that the furrow area for a disc with a diameter of, for example, 350 mm increased from 415 to 4106 mm² when the processing depth increased from 20 to 80 mm. With a fixed depth of 50 mm and alignment angles of $\alpha = 50^\circ$, $\beta = 20^\circ$, varying the disc diameter from 300 to 400 mm changes the furrow area from 1762 to 1935 mm². Reducing the working depth by 5 mm leads to a decrease in the furrow area from 1851 to 1277 mm², while increasing the working depth by the same amount, the furrow area increases to 2516 mm². At the same time, when the angles α and β are reduced to 40° and 15° , respectively, the cross-sectional area of the seed furrow decreases to 1522 mm².

Thus, the method of boundary estimates of the influence of the seed furrow profile on the energy characteristics

of the seeder proposed in this publication is the main scientific and applied achievement of this work, and the methodological approach on the example of disc coulters with the help of appropriate analysis allows optimising the configuration of the working surfaces of disc tillage tools in real-world conditions. The main difficulty in this case is the need to properly take into account the rather different conditions associated with the geometry of specific working surfaces of the disc type, soil condition, size and weight of the sown seeds, the energy used, the peculiarities of agricultural technology, etc. The presented information needs to be generalised and extended to other agricultural tillage tools, which determines the directions of further research on this topic.

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**Підвищення енергоефективності дводискових сошників
на основі методу граничних оцінок впливу профілю посівної борозни**

Анотація. Актуальність дослідження полягає у світовій необхідності підвищення енергоефективності сільськогосподарських знарядь при збереженні високих агротехнічних показників. Метою статті було аналітично оцінити вплив параметрів профілю борозни на експлуатаційні енергетичні характеристики ґрунтообробних знарядь на прикладі дводискових сошників. Методологія ґрунтувалася на геометричному моделюванні робочих компонентів сошника в декартовій системі координат, виведенні параметричних рівнянь контурів борозни та аналітичному обчисленні площі її поперечного перерізу залежно від глибини обробітку, діаметра дисків і кутів їх встановлення. У ході дослідження було встановлено, що площа борозни для дисків діаметром 350 мм зростала від 415 мм² до 4106 мм² зі збільшенням глибини обробітку від 20 мм до 80 мм. За фіксованої глибини 50 мм і кутів $\alpha = 50^\circ$, $\beta = 20^\circ$, площа борозни змінювалася від 1762 мм² до 1935 мм² залежно від зміни діаметра дисків від 300 мм до 400 мм. Було запропоновано квадратичну апроксимацію для опису цієї залежності. Результати показали, що зменшення глибини обробітку з 50 мм до 45 мм зменшувало площу борозни з 1851 мм² до 1277 мм², а її збільшення до 55 мм призводило до зростання площі до 2516 мм². Також було продемонстровано вплив кутів встановлення дисків: при зменшенні до $\alpha = 40^\circ$ і $\beta = 15^\circ$ площа борозни зменшувалася до 1522 мм². Запропонований підхід дозволив здійснити подальшу оптимізацію конфігурації сошників у реальних умовах. Методика, представлена в даній публікації, дозволяє визначити найбільш раціональну конфігурацію ґрунтообробних знарядь для існуючих обставин шляхом проведення відповідного аналізу

Ключові слова: енергоефективність сільськогосподарської техніки; дискові ґрунтообробні знаряддя; математичне моделювання; автоматизоване проектування; комп'ютерні інформаційні технології