

Rakun J.

PhD, Associate Professor

*University of Maribor***Ракун Ю.**

доктор філософії, доцент

*Маріборський університет***УДК 631.3:631.171****DOI: 10.37128/2306-8744-2026-3-8****RESEARCH ON THE INFLUENCE OF DESIGN AND TECHNOLOGICAL PARAMETERS OF PRECISION AGRICULTURE EQUIPMENT ON THE QUALITY OF TECHNOLOGICAL OPERATIONS**

The article presents a theoretical investigation of the influence of design and technological parameters of precision agriculture equipment on the quality of technological operations. The main parameters determining machine performance are analysed, including positioning accuracy, operating speed, working width, actuator response time, geometric arrangement of working elements and metering accuracy. Particular attention is paid to the interaction between the navigation system, control system, actuator and working element, since operation quality depends on their coordinated performance. Analytical relationships are derived for spatial delay, transverse displacement of outer working elements, overlap and skip coefficients, and a comprehensive quality index. Numerical modelling is used to establish the effect of travel speed and actuator response time on spatial delay and the influence of heading-angle error and machine geometry on transverse displacement. The results show that increasing travel speed causes a proportional increase in spatial delay when actuator response time remains unchanged. Even small heading-angle errors can cause considerable displacement of outer working elements as the distance from the centre of rotation increases. A multi-criteria approach to assessing operation quality is proposed, taking into account positioning error, spatial delay, overlaps, skips and deviation of the actual application rate from the prescribed value. The proposed relationships can be used to substantiate design parameters, operating modes and control-system settings of precision agriculture equipment. The results may be applied to seeding, fertiliser application and spraying machines to reduce technological losses, improve treatment uniformity, optimise resource consumption and increase the efficiency of mechanised agricultural production.

Keywords: precision agriculture, technical equipment, design and technological parameters, technological operation, positioning accuracy, automatic control, operating speed, spatial delay, overlap, skips, variable-rate application, quality index.

RESEARCH ON THE INFLUENCE OF DESIGN AND TECHNOLOGICAL PARAMETERS OF PRECISION AGRICULTURE EQUIPMENT ON THE QUALITY OF TECHNOLOGICAL OPERATIONS © 2026 by Rakun J. is licensed under CC BY 4.0

Introduction. Modern agricultural production is characterised by increasing requirements for the productivity of machine-tractor units, the rational use of material resources and the quality of technological operations. One of the most promising approaches to improving the efficiency of mechanised processes is the implementation of precision agriculture technologies, which rely on

spatially referenced data on field conditions and automated control of operational processes.

The quality of technological operations is largely determined by the accuracy of machine movement, the stability of the operating parameters of working elements, and the ability of the technical system to respond promptly to changes in the technological task. The application of satellite navigation systems, automatic guidance systems,



section control systems and variable-rate application technologies makes it possible to reduce skips and overlaps, optimise the consumption of technological materials and increase machine productivity [1].

At the same time, improving the accuracy of an individual technical component does not always result in a proportional improvement in the overall quality of the technological operation. High positioning accuracy cannot compensate for a significant response time of an actuator, while an increase in operating speed may lead to greater spatial delay in the control system. Similarly, increasing the working width of an agricultural unit improves its productivity but simultaneously imposes more stringent requirements on positioning accuracy and control performance [2].

Thus, an important scientific and practical task is to determine the nature of the influence of the design and technological parameters of precision agriculture equipment on the quality indicators of technological operations and to establish the conditions for their rational combination in order to ensure the high efficiency of mechanised agricultural processes.

Review of recent research and publications. The development of precision agriculture technologies has been accompanied by the continuous improvement of technical systems for navigation, automatic control and monitoring of technological processes. A considerable body of research has focused on determining the accuracy of GNSS positioning for agricultural machinery and assessing the impact of navigation errors on the trajectories of machine-tractor units [3].

Studies have established that the application of high-precision satellite positioning systems, particularly RTK technologies, can significantly reduce the lateral deviation of an agricultural unit from its prescribed trajectory. This is especially important when performing operations involving a large number of repeated passes, where even minor positioning errors may accumulate in the form of overlaps or skips [1, 3].

However, the accuracy of the navigation system is only one of the factors determining the quality of unit operation. The actual position of the working elements is influenced by the design parameters of the machine, including the distance between the positioning point and the working element, the working width, the geometric parameters of the unit, the type of connection to the power unit and the characteristics of the running gear. Operating speed is another important technological factor: an increase in speed improves productivity but simultaneously increases the requirements for the response speed of automatic control systems [4, 5].

Actuation systems are inherently characterised by a time delay between the

generation of a control command and the actual change in the operating mode of the working element. Consequently, an increase in travel speed while maintaining a constant response time results in a proportional increase in spatial delay. Variable-rate application systems and automatic section control systems are particularly sensitive to this effect [5, 8, 9].

The reviewed research findings indicate that the quality of a technological operation is determined by the complex interaction of the navigation, control and actuation subsystems. Nevertheless, a comprehensive theoretical assessment of the influence of design and technological parameters on spatial accuracy and quality indicators still requires further development.

Research Objective and Tasks. The objective of this study is to investigate theoretically the influence of the design and technological parameters of precision agriculture equipment on the quality of technological operations and to identify the main factors that determine the spatial accuracy of machine-tractor units.

To achieve this objective, the following tasks are set:

1. to formalise the main design and technological parameters affecting operation quality;
2. to derive analytical relationships for spatial delay, transverse displacement and overlap/skip coefficients;
3. to introduce a comprehensive quality index that integrates positioning error, spatial delay, overlaps, skips and rate deviation;
4. to perform numerical modelling and construct illustrative tables and graphs for typical operating conditions.

Materials and methods.

The quality of a technological operation performed by precision agriculture equipment is determined by a combination of design and technological parameters. The principal parameters include:

- positioning accuracy (GNSS / RTK);
- operating travel speed;
- working width;
- actuator response time;
- structural arrangement of the working elements relative to the positioning and control points;
- parameters of the working elements;
- accuracy of technological material metering.

The interaction between these factors can be represented by the sequential chain:

positioning system → control system → actuator → working element → technological result.

The spatial position of the agricultural unit is determined by the navigation system. Deviations of the actual coordinates from the prescribed

coordinates result in a displacement of the trajectory of the working elements. The absolute positioning error can be expressed as:

$$\Delta p = \sqrt{\Delta x^2 + \Delta y^2}, \quad (1)$$

where Δx and Δy are the errors in determining the position along the longitudinal and transverse axes, respectively.

For technological operations involving multiple parallel passes, the transverse component Δy is of primary importance: it directly determines the width of untreated strips or the extent of repeated treatment (Fig. 1).

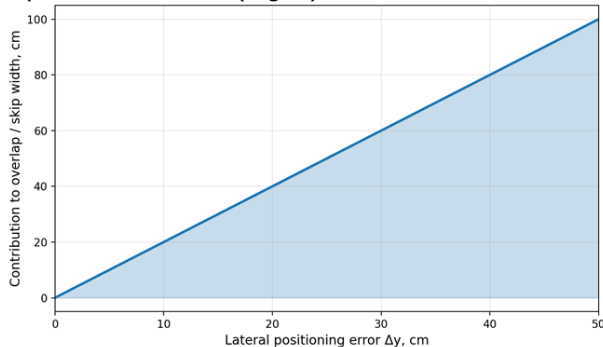


Fig. 1. Effect of lateral positioning error on overlap / skip width

Operating speed is one of the key technological parameters. Increasing the operating speed results in higher theoretical productivity:

$$W = 0.1 \cdot B \cdot V, \quad (2)$$

where W is the theoretical productivity, ha/h; B is the working width, m; V is the travel speed, km/h.

However, an increase in V simultaneously increases the requirements for automatic control systems and actuators. The spatial delay (the distance travelled during the response time of the actuation system) is given by:

$$L_s = V \cdot \frac{t_r}{3.6}, \quad (3)$$

where L_s is the spatial delay, m; V is the travel speed, km/h; t_r is the actuator response time, s.

For example, at a response time $t_r = 2$ s and a travel speed of 6 km/h the spatial delay is approximately 3.33 m; at 12 km/h it increases to 6.67 m. Therefore, any increase in productivity achieved by raising travel speed must be accompanied by a corresponding reduction in actuator response time (Fig. 2 and Fig. 3).

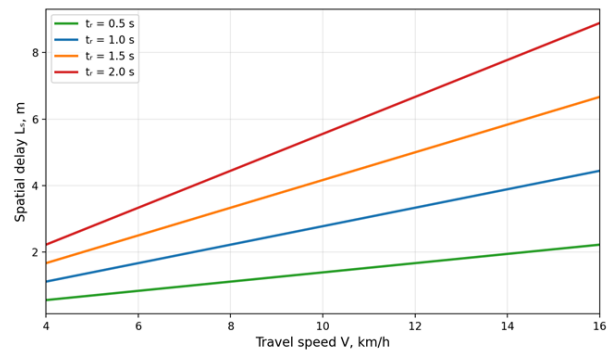


Fig. 2. Spatial delay as a function of travel speed and response time

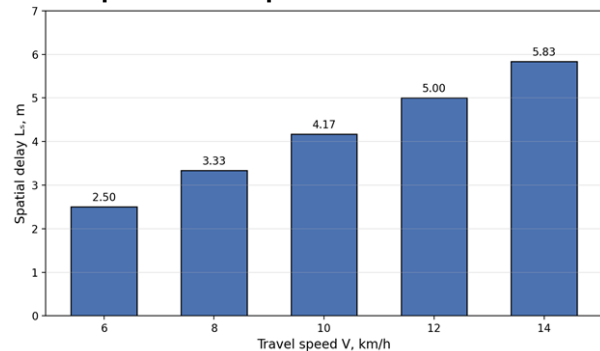


Fig. 3. Spatial delay at different travel speeds ($t_r = 1.5$ s)

The working width directly determines the productivity of the agricultural unit. At the same time, for units with a large working width even a small angular or transverse deviation may result in a significant displacement of the outermost working elements [6].

If the agricultural unit rotates through an angle θ relative to the intended heading, the transverse displacement of a working element located at a distance L from the instantaneous centre of rotation can be approximated as:

$$\Delta y = L \cdot \sin \theta \approx L \cdot \theta \quad (4)$$

Consequently, the structural arrangement of the working elements relative to the control point and the geometric parameters of the unit must be taken into account when designing automatic guidance systems (Fig. 4).

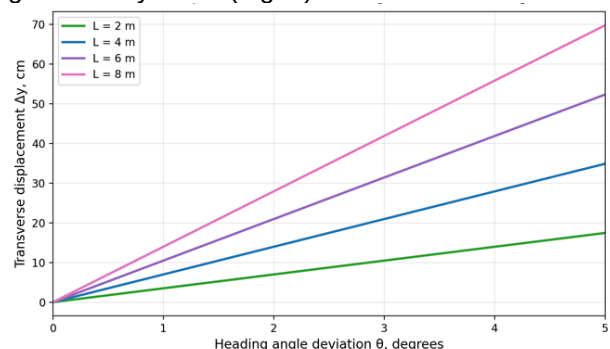


Fig. 4. Transverse displacement of an outer working element versus heading-angle error

Of particular importance is the distance between the GNSS receiver antenna, the control point and the working element. The structural configuration of the agricultural unit should therefore account for the geometric relationship between:

- the positioning point (antenna);
- the centre of rotation of the machine;
- the control point;
- the working elements.

This is especially critical for trailed and semi-trailed implements, in which the working elements may be located at a considerable distance from the attachment point to the tractor [9].

One of the most informative indicators of the performance quality of precision agriculture equipment is the extent of overlaps and skips. The overlap coefficient can be defined as:

$$K_o = \left(\frac{S_o}{S} \right) \cdot 100 \%, \quad (5)$$

and the skip coefficient as:

$$K_s = \left(\frac{S_s}{S} \right) \cdot 100 \%, \quad (6)$$

where S_o is the overlap area, S_s is the skip area and S is the total treated area.

An increase in overlaps results in excessive consumption of seeds, fertilisers or plant-protection products, whereas skips may adversely affect the technological outcome and the uniformity of field treatment. The optimal operating mode is therefore the one that minimises the sum $K_o + K_s$ [10]. Illustrative dependencies of the coefficients on travel speed are shown in Fig. 5.

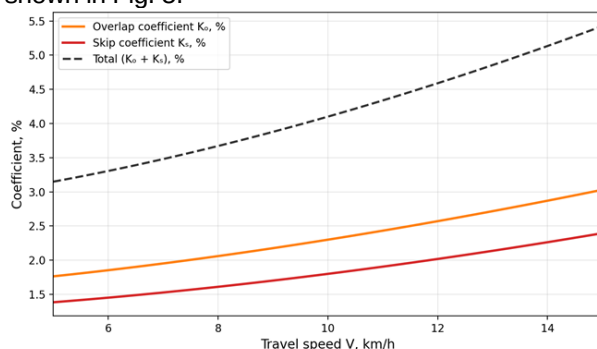


Fig. 5. Overlap and skip coefficients versus travel speed (illustrative model)

Based on the factors considered above, the quality of a technological operation can be assessed by means of a comprehensive indicator that integrates the principal sources of error:

$$Q = f(\Delta p, L_s, K_o, K_s, \Delta q), \quad (7)$$

where Δp is the positioning error; L_s is the spatial delay; K_o and K_s are the overlap and skip coefficients; Δq is the relative deviation of the actual application rate from the prescribed rate.

A convenient normalised form (higher values correspond to better quality) is:

$$Q = 100 \cdot \exp \left(-\alpha \cdot \Delta p - \beta \cdot L_s - \gamma \cdot (K_o + K_s) - \delta \cdot |\Delta q| \right), \quad (8)$$

where α , β , γ , δ are positive weighting coefficients that reflect the relative importance of each error source for a given technological operation. The resulting quality surface (Fig. 6) clearly shows that high quality can be maintained only within a limited region of low positioning error and moderate travel speed.

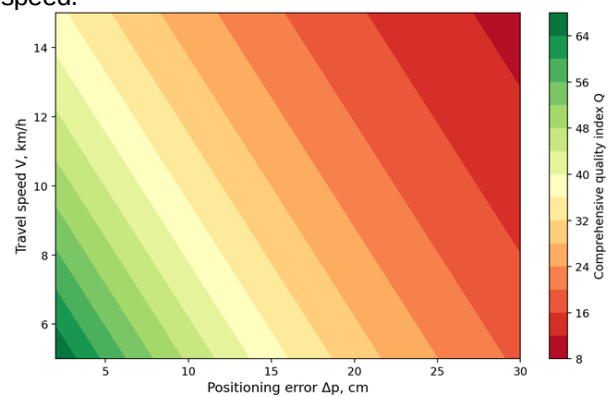


Fig. 6. Comprehensive quality index versus positioning error and travel speed conclusions.

To illustrate the derived relationships, numerical calculations were performed for a typical range of operating conditions. Table 1 presents the spatial delay for different combinations of travel speed and actuator response time.

Table 1

Spatial delay L_s (m) as a function of travel speed and response time

V, km/h \ t_r , s	0.5	1.0	1.5	2.0	2.5
6	0.83	1.67	2.50	3.33	4.17
8	1.11	2.22	3.33	4.44	5.56
10	1.39	2.78	4.17	5.56	6.94
12	1.67	3.33	5.00	6.67	8.33
14	1.94	3.89	5.83	7.78	9.72
16	2.22	4.44	6.67	8.89	11.11

Table 2 illustrates the transverse displacement of the outermost working element for

different heading-angle errors and distances from the centre of rotation.

Table 2

Transverse displacement Δy (cm) of an outer working element

θ , deg \ L, m	2	4	6	8
0.5	1.7	3.5	5.2	7.0
1.0	3.5	7.0	10.5	14.0
1.5	5.2	10.5	15.7	20.9
2.0	7.0	14.0	20.9	27.9
3.0	10.5	20.9	31.4	41.9
5.0	17.4	34.9	52.3	69.8

working widths can produce transverse displacements of several tens of centimetres, which are comparable to or larger than typical RTK positioning errors. Consequently, geometric configuration and guidance-system tuning must be considered jointly with navigation accuracy.

The analysis shows that improving the quality of technological operations cannot be achieved by optimising a single parameter in isolation. High positioning accuracy is necessary but not sufficient; it must be matched by an adequately fast actuation system and a geometrically favourable arrangement of working elements. Likewise, any increase in travel speed or working width must be accompanied by a corresponding improvement in response time and trajectory stability.

A practical design and setting rule can be formulated as follows: the product of travel speed and response time (i.e. the spatial delay L_s) should not exceed a prescribed technological tolerance L_{tol} that depends on the required application accuracy and the characteristics of the working element. Simultaneously, the expected transverse displacement $L \cdot \theta_{max}$ should remain within the same tolerance band.

Conclusions. 1. The quality of technological operations performed by precision agriculture equipment is determined by the complex interaction of positioning accuracy, operating speed, working width, actuator response time and the geometric arrangement of working elements.

2. Analytical expressions for spatial delay ($L_s = V \cdot t_r / 3.6$), transverse displacement ($\Delta y = L \cdot \sin \theta$) and overlap/skip coefficients have been derived, providing a quantitative basis for assessing the influence of each parameter.

3. A comprehensive quality index Q that integrates positioning error, spatial delay, overlaps, skips and rate deviation has been proposed, enabling a shift from single-parameter evaluation to system-level assessment of the “navigation–control–actuator–working element” chain.

4. Numerical modelling confirms that spatial delay and transverse displacement grow rapidly with increasing speed and working width, respectively; therefore any productivity gain must be accompanied by improved response time and guidance accuracy.

5. Further research should focus on experimental identification of the weighting

coefficients of the quality index for specific operations (seeding, fertiliser application, spraying) and on the integration of the proposed relationships into on-board decision-support systems.

References

1. Radočaj, D., Plaščak, I., Heffer, G., & Jurišić, M. (2022). A Low-Cost Global Navigation Satellite System Positioning Accuracy Assessment Method for Agricultural Machinery. *Applied Sciences*, 12(2), 693. <https://doi.org/10.3390/app12020693>.
2. Zhang, X., et al. (2020). Positioning Accuracy Comparison of GNSS Receivers Used for Mapping and Guidance of Agricultural Machines. *Agronomy*, 10(7), 924.
3. Bacco, M., et al. (2023). Global Navigation Satellite Systems as State-of-the-Art Solutions in Precision Agriculture: A Review of Studies Indexed in the Web of Science. *Agriculture*, 13(7), 1417. <https://doi.org/10.3390/agriculture13071417>.
4. Shi, Y., Hu, Z., Wang, X., Odhiambo, M. O., & Ding, W. (2018). Motion analysis and system response of fertilizer feed apparatus for paddy variable-rate fertilizer spreader. *Computers and Electronics in Agriculture*, 153, 239–247.
5. Sharipov, G. M., Heiß, A., Griepentrog, H. W., & Paraforos, D. S. (2020). Evaluation of Centrifugal Spreader Response to Variable Rate Application by Using Task File Data. *IFAC-PapersOnLine*, 53(2). <https://doi.org/10.1016/j.ifacol.2020.12.213>.
6. Mizik, T. (2023). How can precision farming work on a small scale? A systematic literature review. *Precision Agriculture*, 24, 384–406. <https://doi.org/10.1007/s11119-022-09934-y>.
7. Shockley, J. M., Dillon, C. R., & Stombaugh, T. S. (2011). The economic and environmental impacts of precision agriculture technologies. *Precision Agriculture*.
8. Fulton, J. P., et al. (2011). Automatic Section Control Technology from Planters. Alabama Cooperative Extension System.
9. Stombaugh, T. S., Zandonadi, R., & Dillon, C. R. (2008). Assessing the potential of automatic section control. *Proceedings of the 9th International Conference on Precision Agriculture*.



10. Miller, P. C. H., & Butler Ellis, M. C. (2000). Effects of formulation on spray drift. Pesticide Application..

ДОСЛІДЖЕННЯ ВПЛИВУ КОНСТРУКТИВНО-ТЕХНОЛОГІЧНИХ ПАРАМЕТРІВ ТЕХНІЧНИХ ЗАСОБІВ ТОЧНОГО ЗЕМЛЕРОБСТВА НА ЯКІСТЬ ВИКОНАННЯ ТЕХНОЛОГІЧНИХ ОПЕРАЦІЙ

У статті представлено теоретичне дослідження впливу конструктивно-технологічних параметрів технічних засобів точного землеробства на якість виконання технологічних операцій. Проаналізовано основні параметри, що визначають ефективність роботи машин, зокрема точність позиціонування, робочу швидкість, ширину захвату, час реакції виконавчих механізмів, геометричне розташування робочих елементів і точність дозування. Особливу увагу приділено взаємодії навігаційної системи, системи керування, виконавчого механізму та робочого органу, оскільки якість виконання операції залежить від узгодженості їхньої роботи. Отримано аналітичні залежності для визначення просторової затримки, поперечного зміщення крайніх робочих елементів, коефіцієнтів перекриття та пропусків, а також комплексного показника якості. За допомогою чисельного моделювання встановлено вплив швидкості руху та часу реакції виконавчого механізму на просторову затримку, а також вплив похибки курсового кута й геометричних параметрів машини на

поперечне зміщення робочих елементів. Результати показують, що зі збільшенням швидкості руху за незмінного часу реакції виконавчого механізму просторове запізнення зростає пропорційно. Навіть незначні похибки курсового кута можуть спричиняти суттєве зміщення крайніх робочих елементів зі збільшенням їх відстані від центра повороту. Запропоновано багатокритеріальний підхід до оцінювання якості виконання технологічних операцій, який враховує похибку позиціонування, просторову затримку, перекриття, пропуски та відхилення фактичної норми внесення від заданого значення. Запропоновані залежності можуть бути використані для обґрунтування конструктивних параметрів, режимів роботи та налаштувань систем керування технічних засобів точного землеробства. Отримані результати можуть бути застосовані для посівних машин, машин для внесення добрив і обприскувачів з метою зменшення технологічних втрат, підвищення рівномірності обробітку, оптимізації використання ресурсів та підвищення ефективності механізованого сільськогосподарського виробництва.

Ключові слова: точне землеробство, технічні засоби, конструктивно-технологічні параметри, технологічна операція, точність позиціонування, автоматичне керування, робоча швидкість, просторова затримка, перекриття, пропуски, диференційоване внесення, показник якості.

Відомості про автора

Ракун Юрій - доктор філософії (PhD), доцент, факультет сільського господарства та наук про життя, Маріборського університету, Словенія. E-mail: jurij.rakun@um.si. ORCID: <https://orcid.org/0000-0001-9005-3461>.

Rakun Jurij - PhD, Associate Professor, Faculty of Agriculture and Life Sciences, Slovenia, University of Maribor. E-mail: jurij.rakun@um.si. ORCID: <https://orcid.org/0000-0001-9005-3461>

Стаття надійшла 27.07.2026

Стаття прийнята 06.08.2026

Опубліковано 12.10.2026