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Editors office address:

National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony, Kyiv, Ukraine
Tel.: +38(044)-258-42-63
E-mail: info@technicalscience.com.ua
<https://technicalscience.com.ua/en>

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Національний університет біоресурсів і природокористування України

03041, вул. Героїв Оборони, 15, м. Київ, Україна

Тел.: +38(044)-258-42-63

E-mail: info@technicalscience.com.ua

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Yuriy Romasevych*

Doctor of Technical Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0001-5069-5929>

Yaroslav Hubar

Postgraduate Student
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0009-0000-3651-866X>

Synthesis of the optimal acceleration mode of the tower crane slewing mechanism

Abstract. The high performance of cranes is one of the main requirements for construction of buildings and constructins. Tower cranes usually perform such operations. One of the most effective ways to achieve this requirement is to eliminate pendulum oscillations of the load on the flexible suspension for tower cranes in the shortest possible time. Therefore, this article aimed to obtain a general solution to the problem of optimal performance control during the acceleration of the crane's slewing mechanism. A dynamic system model of the tower crane was presented, boundary conditions and optimisation criteria were described, and a torque constraint was introduced. The original problem was reduced to the problem of unconstrained optimisation of a nonlinear function. The problem was solved multiple times, in which the mass of the load m , the length of the flexible suspension l , and the boom extension range r were varied within certain limits. The VCT-PSO optimisation algorithm was used to find solutions. Based on the obtained solutions, a data set for training the artificial neural network (training set) and a data set for testing its operation (test set) were formed. There were used a feedforward neural network to solve the problem of predicting the moments of control switching. Three inputs (corresponding to the parameters m , r , l), three outputs (corresponding to the moments of control switching), and three hidden layers with five neurons in each were used. The neural network was trained using the ADAM method. The results of estimating the quality of the prediction of the control switching moments were determined, and the plots of estimation errors were presented. The high quality of the approximation of the solution surface of the problem using the artificial neural network was established. The analysis of the system motion dynamics under optimal control was carried out, which demonstrated that the system motion indicators were least affected by the mass of the load m and most affected by the length of the flexible suspension l

Keywords: tower crane; slewing mechanism, optimal control; pendulum oscillations of the load; artificial neural network

INTRODUCTION

People widely use tower cranes for load movement on construction sites. To enhance the efficiency of tower cranes, they must quickly move load while eliminating load oscillations on a flexible suspension at the end of the transitional

movement mode (acceleration/braking). Many researchers have worked on developing optimal modes of motion for this mechanism. In work by V.O. Kovalenko (2021) the problem of optimal control of tower crane rotation was set

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*Corresponding author



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to minimise the duration of the work cycle. This problem was solved using the principle of maximum (Pucci, 2004; Kiianovskyi & Kiyanovska, 2022). According to V.V. Svirgun (2022) a structural system diagram for optimal control of the mechanisms for changing the load outreach and crane rotation was developed, along with recommendations regarding its hardware part. In practice, optimal performance control laws were implemented, including eliminating load oscillations after the crane stops and precise load positioning with the minimum number of control stages in the shortest time. In the work by Y.M. Al-Rawashdeh (2023), a framework was presented that enables designing kinodynamical reference trajectories and detecting the flexible modes of uncertain systems while in motion. In the work by A.O. Okun (2021) the problem of optimising load movement of a load on a flexible suspension over a given distance was considered. To construct the control algorithm for the “trolley-load” system, phase plane methods using poles of corresponding transfer functions were applied. In work of O.O. Kovalenko *et al.* (2022) the problem of identifying control laws for the slewing mechanism of a jib crane was solved using the maximum principle. An algorithm for finding optimal performance control was found and described. The law of optimal movement of the slewing mechanism of a laboratory jib crane was calculated.

Zh. Liu *et al.* (2021) presented the development of an algorithm to eliminate the oscillations of a ship crane based on a constructed mathematical model. Using the AMESim-ADAMS platform, the problem was solved. It simulates the load oscillations of a ship crane in simulated deck movement conditions. H. Ouyang *et al.* (2021) researched controlling rotary crane systems. A method for implementing the positioning of the boom and eliminating the oscillation of the moving load by a rotary crane was proposed. The presented boom positioning trajectory can be calculated online. In the study by Z. Yu *et al.* (2021) optimising bridge crane control using a fuzzy PID controller was considered. The researchers proved that the fuzzy PID controller surpasses the traditional PID controller in positioning accuracy, elimination of load oscillations, and efficiency of obstacle avoidance.

This paper aimed to design the optimal time-efficient control mode for the tower crane slewing mechanism. The mandatory condition, which was associated with needed optimal control, was the elimination of load pendulum oscillations. The originality of the presented work is a new approach to optimal control design, which is based on approximation features of an artificial neural network (ANN). It, in turn, allows to generate of optimal control for a wide range of values of dynamical system “crane-load” parameters. Thus, ANN may be considered as a solver of the optimal control problem in a general sense.

MATERIALS AND METHODS

For the research, a two-mass dynamic model of the crane slewing mechanism was adopted (Fig. 1) (Kang & Miranda, 2004).

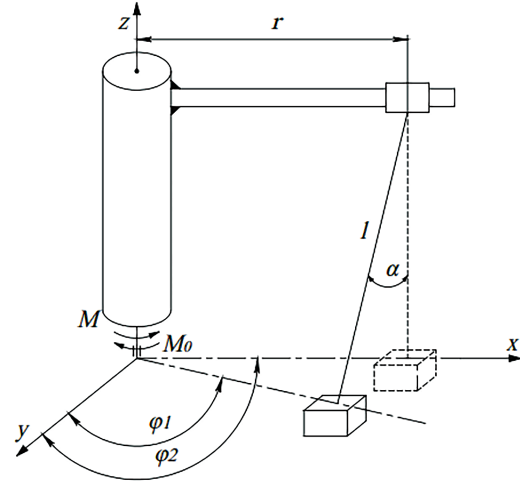


Figure 1. Dynamic model of the jib crane slewing mechanism

Note: M_0 – the combined resistance torque that arises in the crane rotary part; M – the combined motor torque driving the slewing mechanism of the crane; m – the mass of the load; l – the length of the cable; r – the length of the crane’s boom; I – the moment of inertia of the elements of the drive mechanism of slewing mechanism and the rotating tower, reduced to the crane rotary axis; ϕ_1 – angular coordinate of crane slewing; ϕ_2 – angular coordinate of load position; x , y , and z – Cartesian coordinates

Source: compiled by the authors

The generalised coordinates of the dynamic model were the angular coordinates of rotation, reduced to the rotation axis of the crane elements of the slewing mechanism drive and the rotating tower with the boom ϕ_1 and the load ϕ_2 . Thus, in the study, the angular system was the reference. All torques that occur in this system were taken into account. Others (for instance, torques in the plane of the crane) were neglected. The equations of motion corresponding to this model were taken from the work with condition $C \rightarrow \infty$:

$$\begin{cases} M - M_0 \text{sign}(\dot{\phi}_1) = I\ddot{\phi}_1 + mr^2\frac{g}{l}(\phi_1 - \phi_2); \\ \ddot{\phi}_2 = \frac{g}{l}(\phi_1 - \phi_2), \end{cases} \quad (1)$$

where M_0 – the combined resistance torque that arises in the crane rotary part; M – the combined motor torque driving the slewing mechanism of the crane; m – the mass of the load; l – the length of the cable; r – the length of the crane’s boom; I – the moment of inertia of the elements of the drive mechanism of slewing mechanism and the rotating tower, reduced to the crane rotary axis. For the process of starting the slewing mechanism of the jib crane, the following boundary conditions were used:

$$\begin{cases} \phi_1(0) = \dot{\phi}_1(0) = \phi_2(0) = \dot{\phi}_2(0); \\ \phi_1(T) = \dot{\phi}_1(T) = \phi_2(T) = \dot{\phi}_2(T) = \omega, \end{cases} \quad (2)$$

where ω – the rated angular velocity of the crane slewing. The initial conditions mean the system’s movement from

a state of rest, i.e., when there is no movement. The final conditions meant the system's movement at the nominal angular velocity ω in the absence of pendulum oscillations of the load. To conduct optimisation, a performance criterion was used, reflecting the duration of the crane slewing mechanism acceleration:

$$\int_0^T dt \rightarrow \min = T, T = t_1 + t_2 + t_3, \quad (5)$$

where T – the duration of the system movement; t_1, t_2, t_3 – the durations of the first, second, and third stages, respectively. The engine that drives the slewing mechanism of the crane was characterised by its overload capacity, so constraints on the torque were introduced:

$$M_{\min} \leq M \leq M_{\max}, \quad (6)$$

where $M_{\min}$ and $M_{\max}$ – the minimum and maximum values of the driving torques. The asynchronous motor, which is part of the drive of the slewing mechanism of the crane, is characterised by symmetry, hence, the following expression was valid: $M_{\min} = -M_{\max}$. A constraint on the angular velocity of the crane's rotation $\dot{\phi}$ was introduced:

$$0 \leq \dot{\phi}_1 \leq \omega, \quad (7)$$

where the angular velocity must be within the range from 0 to ω . This allowed acceleration to the nominal speed without exceeding it. This, in turn, enabled the rotation of the crane without additional energy expenditure. Since the movement is in one direction, a constraint was introduced that the angular velocity should not be less than zero.

Problems (1)-(5) are pretty complex. Therefore, it was reduced to a problem of unconstrained optimisation. The second equation of the system (1) was twice differentiated concerning time:

$$\ddot{\phi}_1 = \ddot{\phi}_2 + \frac{l}{g} \dot{\phi}_2^{IV}. \quad (8)$$

The substitution of expression (6) into the first equation of system (1) gave:

$$M - M_0 = I(\ddot{\phi}_2 + \frac{l}{g} \dot{\phi}_2^{IV}) + mr^2 \frac{g}{l} (\phi_1 - \phi_2). \quad (9)$$

Taking into account the second equation of system (1), the equation (7) was rewritten as follows:

$$\begin{aligned} M - M_0 &= I \left(\ddot{\phi}_2 + \frac{l}{g} \dot{\phi}_2^{IV} \right) + mr^2 \ddot{\phi}_2 = \\ &= I \ddot{\phi}_2 + \frac{l}{g} I \dot{\phi}_2^{IV} + mr^2 \ddot{\phi}_2 = \frac{l}{g} I \dot{\phi}_2^{IV} + (I + mr^2) \ddot{\phi}_2. \end{aligned} \quad (10)$$

Both sides of expression (8) were divided by the coefficient near the highest derivative of the function ϕ_2 :

$$\frac{M - M_0}{I} \cdot \frac{g}{l} = \dot{\phi}_2^{IV} + \frac{l + mr^2}{I} \cdot \frac{g}{l} \ddot{\phi}_2. \quad (11)$$

The notations were introduced:

$$\Omega_0 = \sqrt{\frac{g}{l}}, \quad (12)$$

$$\Omega = \sqrt{\frac{l + mr^2}{I} \cdot \frac{g}{l}}; M - M_0 = M_{din}. \quad (13)$$

The expression (10) can be rewritten in the following form:

$$\dot{\phi}_2^{IV} + \Omega^2 \ddot{\phi}_2 = \frac{M_{din}}{I} \cdot \Omega_0^2. \quad (14)$$

The acceleration period can be considered a movement in three stages, where the torque M takes a constant value ($M_{\max}$ or $M_{\min}$). This fact allowed obtaining an analytical solution of the differential equation (12) for the i -th stage:

$$\begin{aligned} \phi_2 &= \frac{1}{2I\Omega^2} (\ddot{\phi}_2(\tau_{i-1}) + \ddot{\phi}_2(\tau_{i-1})(t - \tau_{i-1}) + (\ddot{\phi}_2(\tau_{i-1})(t - \tau_{i-1}) + \\ &+ 2(\tau_{i-1})\Omega^2) + M_{din}(-2 + (t - \tau_{i-1})^2 \Omega_0^2 + (-2\ddot{\phi}_2(\tau_{i-1}))m\Omega^2 + \\ &+ 2M_{din}\Omega_0^2)\cos((t - \tau_{i-1})\Omega) - 2\ddot{\phi}_2 m\Omega \sin((t - \tau_{i-1})\Omega)); \\ \tau_0 &= 0, \tau_1 = t_1, \tau_2 = t_1 + t_2, \end{aligned} \quad (15)$$

where τ_{i-1} – the moment of the beginning of the i -th stage of the dynamic system's movement.

The next step in the calculations was to determine the function ϕ_2 for the system's first, second, and third acceleration stages using equation (13).

$$\begin{cases} \phi_2(\tau_0) \rightarrow 0, \dot{\phi}_2(\tau_0) \rightarrow 0, \ddot{\phi}_2(\tau_0) \rightarrow 0, \ddot{\phi}_2(\tau_0) \rightarrow 0, \\ M_{din} \rightarrow (M_{\max} - M_0), \tau_0 \leq t \leq \tau_1; \\ \phi_2(\tau_1) \rightarrow \phi_{2t_1}, \dot{\phi}_2(\tau_1) \rightarrow \dot{\phi}_{2t_1}, \ddot{\phi}_2(\tau_1) \rightarrow \ddot{\phi}_{2t_1}, \ddot{\phi}_2(\tau_1) \rightarrow \ddot{\phi}_{2t_1}, \\ M_{din} \rightarrow (M_{\max} - M_0), \tau_1 \leq t \leq \tau_2; \\ \phi_2(\tau_2) \rightarrow \phi_{2t_1+t_2}, \dot{\phi}_2(\tau_2) \rightarrow \dot{\phi}_{2t_1+t_2}, \ddot{\phi}_2(\tau_2) \rightarrow \ddot{\phi}_{2t_1+t_2}, \\ M_{din} \rightarrow (M_{\max} - M_0), \tau_2 \leq t \leq T. \end{cases} \quad (16)$$

As a result, three solutions corresponding to the three stages of the system's acceleration were obtained. Let us denote them $\phi_{2,1}, \phi_{2,2}, \phi_{2,3}$ (the indices 1, 2 and 3 reflect the corresponding stage number). Having all the solutions for the three stages, the conditions for combining the solutions at the moments τ_1 and τ_2 were set:

$$\begin{cases} \phi_{2,1}(\tau_1) = \phi_{2\tau_1}, \phi_2(\tau_1) = \phi_{2\tau_1}, \dot{\phi}_2(\tau_1) = \dot{\phi}_{2\tau_1}, \ddot{\phi}_2(\tau_1) = \ddot{\phi}_{2\tau_1}; \\ \phi_{2,2}(\tau_2) = \phi_{2\tau_2}, \phi_2(\tau_2) = \phi_{2\tau_2}, \dot{\phi}_2(\tau_2) = \dot{\phi}_{2\tau_2}, \ddot{\phi}_2(\tau_2) = \ddot{\phi}_{2\tau_2}. \end{cases} \quad (17)$$

These calculations allowed finding the function $\phi_{2,3}(t)$. It was not provided here due to its significant volume. Substituting $t \rightarrow t_1 + t_2 + t_3$ into the function $\phi_{2,3}(t)$ allowed to obtain the magnitude of $\phi_{2,3}(T)$, and the magnitude $\dot{\phi}_{2,3}(T)$, $\ddot{\phi}_{2,3}(T)$. They can be presented in the following form:

$$\begin{aligned} \phi_{2,3}(T) &= \frac{1}{2I\Omega^4} \Omega_0^2 (2M_0 - 2M_{\max} - M_0(t_1 + t_2 + t_3)^2 \Omega^2 + \\ &+ M_{\max}(t_1^2 - t_2^2 - 2t_2 t_3 + t_3^2 + 2t_1(t_2 + t_3))\Omega^2 + 4M_{\max} \cos(t_3 \Omega) - \\ &- 4M_{\max} \cos((t_2 + t_3)\Omega) + 2(-M_0 + M_{\max}) \cos((t_1 + t_2 + t_3)\Omega)); \end{aligned} \quad (18)$$

$$\begin{aligned} \dot{\phi}_{2,3}(T) &= \Omega_0^2 (M_{\max}(t_1 - t_2 + t_3)\Omega - M_0(t_1 + t_2 + \\ &+ t_3)\Omega - 2M_{\max} \sin(t_3 \Omega) + 2M_{\max} \sin((t_2 + t_3)\Omega) + \\ &+ (M_0 - M_{\max}) \sin((t_1 + t_2 + t_3)\Omega)); \end{aligned} \quad (19)$$

$$\begin{aligned} \ddot{\phi}_{2,3}(T) &= \Omega_0^2 (-2M_{\max} \cos(t_3 \Omega) + 2M_{\max} \cos((t_2 + t_3)\Omega) + \\ &+ (M_0 + M_{\max})(-1 + \cos((t_1 + t_2 + t_3)\Omega)); \end{aligned} \quad (20)$$

$$\ddot{\phi}_{2,3}(T) = \Omega_0^2(2M_{\max} \sin(t_3\Omega) - 2M_{\max} \sin((t_2 + t_3)\Omega) + (-M_0 + M_{\max}) \sin((t_1 + t_2 + t_3)\Omega)). \quad (19)$$

Taking into account expressions (16)-(19), the conditions that correspond to the final conditions of the system's movement were written: its acceleration to the nominal angular velocity ω and ensuring the absence of pendulum oscillations of the load at the end of acceleration. They were represented in the form of a system of transcendental algebraic equations:

$$\begin{cases} \omega - \dot{\phi}_{2,3}(T) = 0; \\ \ddot{\phi}_{2,3}(T) = 0; \\ \ddot{\phi}_{2,3}(T) = 0. \end{cases} \quad (20)$$

Again, due to the significant volume of the obtained expressions, they were not presented in an expanded form.

To solve the system of transcendental algebraic equations (20), the TE function were construct, which in a certain sense reflects the level of satisfaction of the final conditions (2):

$$\begin{aligned} TE &= \frac{mr^2}{2} \left((\omega - \dot{\phi}_{2,3}(T))^2 + (\ddot{\phi}_{2,3}(T))^2 + \left(\frac{\ddot{\phi}_{2,3}(T)}{\Omega_0^2} \right)^2 \right) = \\ &= \frac{1}{2I^2\Omega^6} mr^2 (\Omega^2\Omega_0^4(-2M_{\max} \cos(t_3\Omega) + 2M_{\max} \cos((t_2 + t_3)\Omega) + \\ &+ (M_0 - M_{\max})(-1 + \cos((t_1 + t_2 + t_3)\Omega)))^2 + \Omega^4(2M_{\max} \sin(t_3\Omega) - \\ &- 2M_{\max} \sin((t_2 + t_3)\Omega) + (-M_0 + M_{\max}) \sin((t_1 + t_2 + t_3)\Omega))^2 + \\ &+ ((-M_{\max}(t_1 - t_2 + t_3) + (M_0(t_1 + t_2 + t_3)))\Omega\Omega_0^2 + 2M_{\max}(\Omega^2 - \\ &- \Omega_0^2)\sin(t_2\Omega) + (M_0 - M_{\max})(\Omega^2 - \Omega_0^2)\sin((t_1 + t_2)\Omega)). \end{aligned} \quad (21)$$

The first term in brackets in expression (21) corresponded to the kinetic 'excess or insufficient energy' of mass m . It showed the deviation of the energy of mass m at the moment $t_1 + t_2 + t_3$ from the value $m\omega^2/2$. The second and third terms in expression (21) were the potential and kinetic energy of the load's (pendulum's) oscillations at the end of the system's acceleration.

Thus, the initial problem (1)-(5) was reduced to the following:

$$\begin{aligned} \underset{t_1, t_2, t_3}{\operatorname{argmin}} \left(\frac{2E}{m\omega^2} + (t_1 + t_2 + t_3) \frac{\Omega}{2\pi} \right), \\ E = \begin{cases} w \cdot TE, & \text{if } TE \geq \Delta; \\ 0, & \text{if } TE < \Delta, \end{cases} \end{aligned} \quad (22)$$

where Δ – a certain conditional energy threshold corresponding to the deviation of the system's state from the desired one at the end of its acceleration, i.e., it is a function that defines the deviation of the final phase coordinates from the final conditions (2): the smaller the Δ , the closer the final phase coordinates are to the final conditions (2) (within this study $\Delta = 10^{-2}$ J); w – a weight coefficient that ensures the importance of minimising TE (set to $w = 10^6$); E – a nonlinear function that reflects the fulfillment of the condition $TE < \Delta$.

The first term in brackets in expression (22) was the system's specific "excess" energy at the end of the system's acceleration. The second was the specific duration of the system's acceleration. Both addends are dimensionless and, therefore, can be added. The exact solution of problem (1)-(5) reduces the first term of criterion (22) to a value that was less than the threshold Δ , when all the final conditions (2) were practically fulfilled. Including the values of w and Δ in the objective function (22) can be explained by a two-stage process of searching for a solution to the problem. In the first stage, the value of E was minimised. The optimisation algorithm searched the minimum T (since $E = 0$) in the second stage. Such a structure of the objective function (22) allowed for the avoidance of false solutions to the original problem (2)-(4). Indeed, at least two such cases can be imagined:

1) $w = 1$, then $t_1 \rightarrow 0$, $t_2 \rightarrow 0$, $t_3 \rightarrow 0$. In this case, the objective function (22) has a global minimum, which equals 1. The second and third terms of TE in brackets (the first line of expression (21)) equaled zero, and only the first term equaled ω ;

2) $\Delta = 0$, then at some stage of minimising the objective function (22), the product $w \cdot TE$ was reduced to a value comparable to t_1 , t_2 and t_3 values. This meant that the requirements for minimising the magnitudes of $w \cdot TE$ and $(t_1 + t_2 + t_3)\Omega/2\pi$ start competing. In this case, there was no guarantee of a complete minimisation of the criterion (3).

To ensure compliance with condition (5), the potentially highest speed of crane rotation during acceleration was found, which was at the end of the first stage when the tower begins to accelerate:

$$\begin{aligned} \dot{\phi}_2(t_1) &= -\frac{1}{I\Omega^3} (M_{\max}(-t_1 + t_2) + M_0(t_1 + t_2))\Omega\Omega_0^2 + 2M_{\max}(\Omega^2 - \\ &- \Omega_0^2)\sin(t_2\Omega) + (M_0 - M_{\max})(\Omega^2 - \Omega_0^2)\sin((t_1 + t_2)\Omega). \end{aligned} \quad (23)$$

The potentially lowest speed of crane rotation during acceleration was found, which was at the end of the second stage when the tower was braking:

$$\dot{\phi}_2(t_1 + t_2) = -\frac{(M_0 - M_{\max})(t_1\Omega\Omega_0^2 + (\Omega^2 - \Omega_0^2))\sin(t_1\Omega)}{I\Omega^3}. \quad (24)$$

Expression (23) was found to fulfill the constraint of not exceeding ω , and expression (24) was found to fulfill the constraint of no crane reversal (absence of negative angular velocity of crane rotation). Further, to take into account the constraints (5), penalty functions were constructed:

$$P_1 = \begin{cases} \frac{\dot{\phi}_2(t_1)}{\omega} \cdot \lambda_1, & \text{if } \dot{\phi}_2(t_1) > \omega; \\ 0, & \text{if } \dot{\phi}_2(t_1) \leq \omega, \end{cases} \quad (25)$$

$$P_2 = \begin{cases} \frac{\dot{\phi}_2(t_1 + t_2)}{\omega} \cdot \lambda_2, & \text{if } \dot{\phi}_2(t_1 + t_2) < 0; \\ 0, & \text{if } \dot{\phi}_2(t_1 + t_2) \geq 0, \end{cases} \quad (26)$$

where λ_1, λ_2 – weight coefficients determining the importance of fulfilling the constraints (5). If the upper or lower constraints were violated, functions P_1 , or P_2 took large

values. Their magnitudes were regulated precisely by the weight coefficients λ_1, λ_2 , which in this study were equal to 10^8 . Thus, the problem (1)-(5) was reduced to the minimisation of the following function:

$$\underset{t_1, t_2, t_3}{\operatorname{argmin}} \left(\frac{2E}{m\omega^2} + (t_1 + t_2 + t_3) \frac{g}{2\pi} + P_1 + P_2 \right). \quad (27)$$

It was necessary to set numerical values for the system to solve the problem (27) (Table 1).

Table 1. Parameters of the “crane-load” system

Parameter	Unit of measurement	Value
m	kg	200-5000
l	m	3-15
r	m	2.5-40
ω	rad/s	0.07
$M_{\max}$	Nm	257142
M_0	Nm	25714
I	kg·m ²	4992364

Source: compiled by the authors

The values of m, l, r in Table 1 were given as ranges. This was necessary to reflect the practical side of the tower crane operation. Its work occurred with different masses of load m , different lengths of flexible suspension l , and different outreach of load r . The limits of the ranges for these values, as was shown in Table 1, correspond to the maximum and minimum values encountered in operating a tower crane.

RESULTS AND DISCUSSION

To solve problem (27), the VCT-PSO optimisation algorithm was used, which is a profound modification of the canonical Particle Swarm Optimisation (PSO) method (Romasevych & Loveikin, 2022). The following settings of this algorithm were used: $c_1 = c_2 = 1.19$, $RC = 5$, $w = 0.72$. Example plots corresponding to the results of solving the problems using the VCT-PSO algorithm were given below. For example, Figure 2 presented a plot of the convergence of function (27) when solving the problem for the following parameters: $m = 600$ kg, $l = 10$ m, $r = 25$ m.

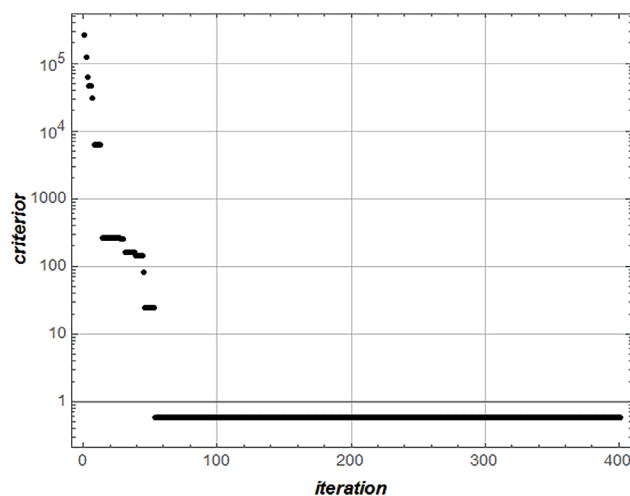


Figure 2. Plot of convergence of function (27) for parameters $m = 600$ kg, $l = 10$ m, $r = 25$ m

Source: compiled by the authors

As can be seen from the plot, the value of the criterion decreased during the first seventy iterations, and from the seventieth to the four-hundredth iteration, function (27) remained unchanged. Overall, this algorithm found solutions for three thousand five hundred ninety-seven problems (for different variants of load mass m , length of flexible suspension l and load outreach r). All of them were presented in the following format: $\{t_1, t_2, t_3, m, r, l\}$. The found solutions were used for training an artificial neural network, which was used to approximate the entire set of solutions to problems (1)-(5).

Calculation of optimisation problem solution each time required a large amount of computation resources. To make the process of values t_1, t_2, t_3 mining much quicker (and implemented in crane control system) an artificial neural network was used. After its training and testing it may be exploited to calculate values t_1, t_2, t_3 for different practical cases of exploitation (varying values m, r, l). From the found solutions to the problems, a data array was formed for training the artificial neural network (training sample) and an array for testing its performance (test sample). Overall, 2886 solutions were selected for training the artificial neural network and 711 for its testing.

This study used a feedforward neural network with 3 inputs (corresponding to parameters m, r, l), 3 outputs (corresponding to values t_1, t_2, t_3) and 3 hidden layers with 5 neurons each.

Each neuron of the artificial neural network was characterised by a “hyperbolic tangent” activation function. The neural network was fully connected, and each neuron received a bias signal. To conduct the training of the artificial neural network, data normalisation was carried out:

$$\tilde{m} = \frac{m - m_{\min}}{m_{\max} - m_{\min}}; \quad \tilde{r} = \frac{r - r_{\min}}{r_{\max} - r_{\min}}; \quad \tilde{l} = \frac{l - l_{\min}}{l_{\max} - l_{\min}}, \quad (28)$$

where $\tilde{m}, \tilde{r}$, and $\tilde{l}$ – the normalised values of the load mass, boom outreach, and the length of the flexible suspension, respectively. Normalised values range was from zero to one.

The neural network training was carried out using the ADAM method (Kingma & Ba, 2015). The batch size

equals 500. How accurately the artificial neural network approximates data needs to be determined. Thus, the RMS error (RMSE) of the prediction of the duration of the system's movement stages was calculated according to the formula:

$$e_{RMS,t1} = \sqrt{\sum_{i=1}^I \left(\frac{E_{t1,i}(t_{1,max} - t_{1,min})}{t_{1,m,i}(t_{1,max} - t_{1,min}) + t_{1,min}} \right)^2} 100\%, \quad (29)$$

where $e_{RMS,t1}$ – the RMS error of the prediction of the duration of the first stage of the system's movement; $E_{t1,i}$ – the i -th error of the prediction of the duration of the first stage of the system's movement; $t_{1,i}$ – the i -th value of the duration of the first stage of the system's movement from the test data sample; $t_{1,max}$ – the maximum value of the duration of the first stage of the system's movement across the entire test sample; $t_{1,min}$ – the minimum value of the duration of the first stage of the system's movement across the

entire test sample; I – the length of the test data sample. Similar calculations were used to estimate the durations of the second and third stages. In addition to the RMS indicators, the maximum errors were also used:

$$e_{max,t1} = \max \left(\left| \frac{E_{t1,i}(t_{1,max} - t_{1,min})}{t_{1,m,i}(t_{1,max} - t_{1,min}) + t_{1,min}} \right| \right) 100\%, \quad (30)$$

where $e_{max,t1}$ – the maximum error in predicting the duration of the first stage of the system's movement. Finding the maximum errors for the second and third stages was carried out with using similar formulas.

The obtained error values were entered into Table 2. Table 2 shows that the values of the RMS errors were insignificant and approximately within one percent. The maximum errors of the 1-st and 3-rd stages (1.44 and 1.63%, respectively) were also minor. Only the maximum error of the second stage stands out at 7.34%.

Table 2. Results of the quality assessment of the prediction of the duration of the dynamic system's movement stages performed by the artificial neural network

Stage number	Errors, %	
	RMS	Maximal
1 st	0.34	1.44
2 nd	1.08	7.34
3 rd	0.41	1.63

Source: compiled by the authors

For clarity of the obtained estimates, Figure 4 presented the plots of the error in the duration of the system's movement (separately for each acceleration stage). The index j indicates the test frame number used for the evaluation. All the calculations that assessed the

dynamics of the system movement under optimal control were conducted using eight parameter variations (Table 3). In Table 3, the following notations were used: $m_{min} = 300$ kg, $m_{max} = 4500$ kg, $r_{min} = 3.75$ m, $r_{max} = 36$ m, $l_{min} = 4.5$ m, $l_{max} = 13.5$ m.

Table 3. Variants of parameter combinations for the assessment of movement dynamics under optimal control

Variant Number	Parameter		
	m	r	l
1	m_{min}	r_{min}	l_{min}
2			l_{max}
3		r_{max}	l_{min}
4			l_{max}
5	m_{max}	r_{min}	l_{min}
6			l_{max}
7		r_{max}	l_{min}
8			l_{max}

Source: compiled by the authors

Calculations were carried out for each of the eight variants using the already trained artificial neural network. For example, a graphical interpretation of the solutions to

problems (1)–(5) only for the first (Fig. 3) were presented. All values on the graphs were normalised, that was, the maximum value was equal to 1, and the minimum value was -1.

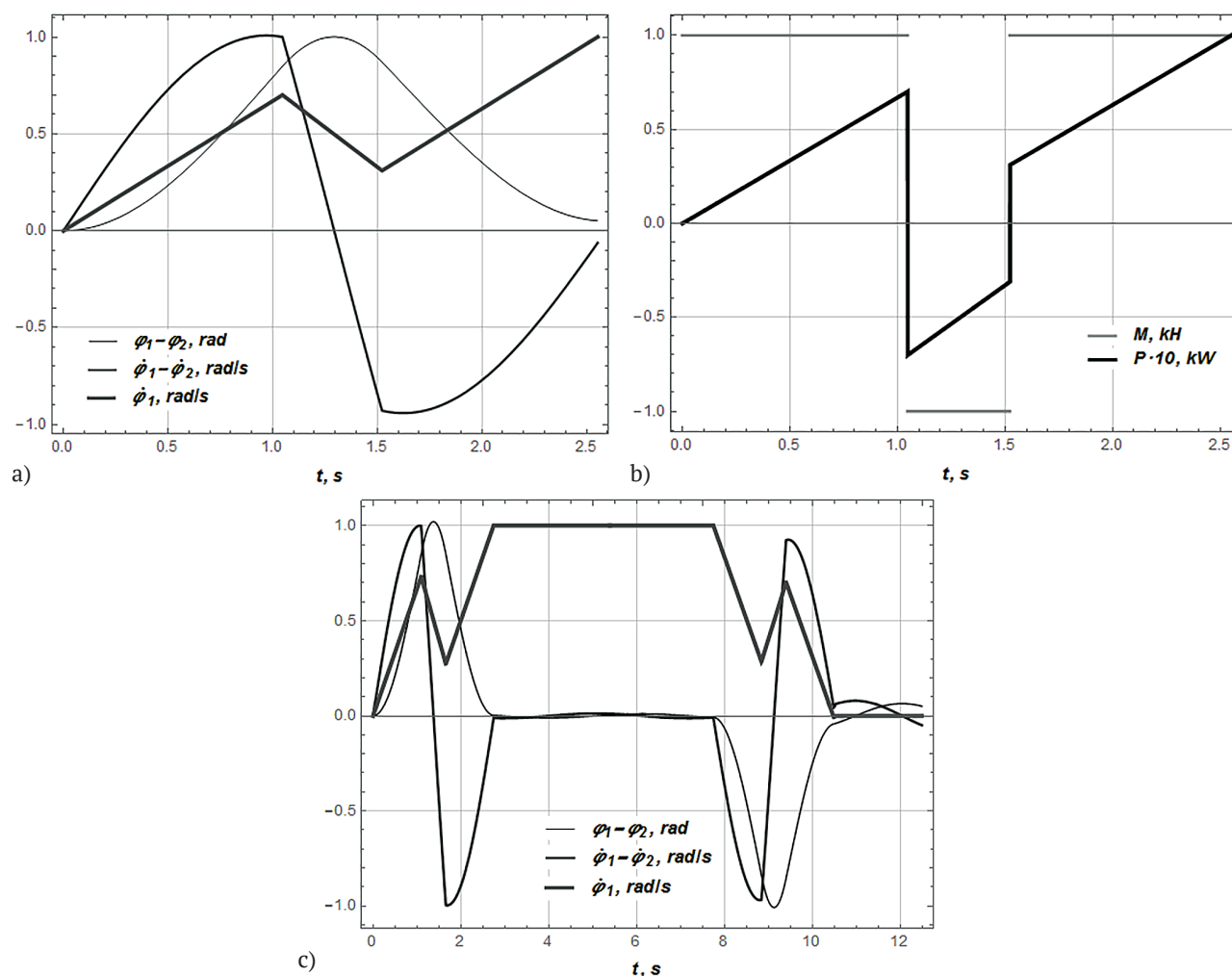


Figure 3. Plots of kinematic, dynamic, and energy characteristics

of the dynamic system's movement corresponding to the first number of parameter variants (Table 3)

Note: a) the angle of cable deviation from the vertical and its first time derivative, as well as the crane's rotation speed during acceleration; b) the driving torque of the crane's drive and the power consumed by the drive during acceleration; c) the angle of cable deviation from the vertical and its first time derivative, as well as the crane's rotation speed during the cycle "acceleration-steady movement – deceleration" and after it

Source: compiled by the authors

Figure 3a presents three plots. The bold black line shows the angular velocity of the system, which was represented as a broken line because during the period from 1.05 seconds to 1.50 seconds, the system brakes, and then after some time, it increases its speed again. The thin black line represented the difference in the speeds of the crane and the load's motion. The gray line represented the difference in the angular positions of the crane and the load.

Figure 3b showed a plots of the system's force characteristics, where the black line represented the power of the crane's slewing mechanism drive during acceleration. As noted above, the system breaks from 1.05 seconds to 1.50 seconds, so the power plots changed sign to the opposite. At this point, the drive operates in a regenerative mode, i.e., it changed its operating mode: instead of working as a motor, it started working as a generator, producing

energy. It is necessary to use a specific frequency converter to implement such a mode. The converter has to recuperate energy into the network (with a reverse inverter).

In order to prove the efficiency of the optimal control in the sense of pendulum oscillations elimination, Figure 3c gave the functions of the system movement during the cycle "acceleration-steady movement – deceleration" and after it (during 5 s). It clearly shows almost complete elimination of oscillations. In the plot in Figure 3c are caused by the fact that only the minimum values of the load mass, the length of the flexible suspension, and the boom outreach were taken for calculation. An analysis of the assessment indicators of the system's motion under optimal control for each of the eight variants was also carried out, which are presented in Table 4. Analysing the data in Table 4, brought that the duration of the first and third stages have almost identical values.

Table 4. Assessment indicators of the dynamics of optimal control of the “crane-load” system’s movement

Indicator	Variant number							
	1	2	3	4	5	6	7	8
Duration of the 1-st stage, s	1.045	1.477	1.063	1.504	1.061	1.502	1.121	1.532
Duration of the 2-nd stage, s	0.481	1.182	0.470	1.172	0.474	1.176	0.395	1.115
Duration of the 3-rd stage, s	1.026	1.465	1.058	1.498	1.057	1.495	1.115	1.530
The amplitude of the angle of cable deviation from the vertical, rad	0.023	0.062	0.024	0.063	0.024	0.063	0.023	0.063
The maximum difference in rotation speeds of the crane and the load, rad/s	0.029	0.054	0.029	0.055	0.028	0.055	0.027	0.054
The maximum power in reverse mode (at the beginning of the second stage), kW	12.45	17.56	12.60	17.88	12.55	17.83	12.36	17.61
The RMS of the angle of cable deviation from the vertical, rad	0.013	0.035	0.013	0.036	0.013	0.036	0.013	0.035
The RMS of the difference in rotation speeds of the crane and the load, rad/s	0.021	0.033	0.021	0.034	0.021	0.034	0.021	0.034
The RMS of the crane drive’s power, kW	9.774	10.27	10.07	10.59	9.941	10.48	9.892	10.11
RMS of the drive torque of the crane, kNm	257.1							

Source: compiled by the authors

When analysing the duration across all 3 stages, it was evident that the values of the duration of individual stages in the odd variants were less than those corresponding to the even variants. This can be explained by the fact that different lengths of flexible suspension were used for these variants. The amplitude of the angle of cable deviation from the vertical for even variants have much bigger values, than those, which reflected to the odd variants. The same may be stated (but to a somewhat lesser extent) for the maximum difference in rotation speeds of the crane and the load. The reason of this outcome may be found in Table 3. Indeed, in the even variants $l_{\max}$ value was involved, for the odd ones – $l_{\min}$. Thus, the more l value, the more amplitudes of the load oscillations. This conclusion may be generalised to the RMS values (Table 4) as well. RMS of the drive torque of the crane is the same for all variants because the crane drive was operated at the extreme (maximum or minimum) torque throughout the duration of the system’s acceleration.

One advantage of the fuzzy PID controller is its insensitivity to system internal parameter changes. In work Yu. Qian *et al.* (2021) the adaptive control of a marine crane based on a neural network was described. The developed algorithm improves the efficiency of obstacle avoidance and provides high-performance control, accurate load positioning, and quick reduction of pendulum oscillations of the load. In work by Yu. Romasevych *et al.* (2022) the synthesis of optimal control of the “crane-load” system was considered. The article examined problem of optimal control of the system, which ensures the elimination of load oscillations, minimisation of energy consumption, and maximum crane work productivity. The problem was solved by minimising the MISO function. An optimisation criterion was developed for this, which was minimised using a modified particle swarm (ME-D-PSO). In the work by T.-S. Wu *et al.* (2015), a control scheme based on Lyapunov stability was proposed to suppress the influence of external disturbances, eliminate fuzzy approximation errors,

and ensure that the swaying motion of the tower crane system converges to the neighborhood of zero. In work by B.I. Mokin *et al.* (2020) a law of optimal control for one class of objects with time- and space-varying parameters (characteristics of the load movement process and the effect of longitudinal oscillations of the crane boom) was synthesised. An integral functional criterion with an integrand of the square of the deviations of the absolute angular velocity of the drive electric motor of the hoisting crane from its set function was used as the optimisation criterion. It showed that implementing the synthesised law of optimal control of the crane’s electric drive achieves such characteristics of the load movement process that prevent the destruction of both the loads and their destination points, as the load movement process occurs without impact collisions. In work by I. Jebellat & I. Sharf (2023) two novel motion planning solutions for manipulator arms, by utilising the dynamic programming framework and collision-free paths time-dependent waypoints, were proposed. G.-H. Kim *et al.* (2021) offered a neural network-based robust antisway control method for the control problem of industrial cranes. To address the uncertainties in the system parameters and hydrodynamic forces, a neural network-based estimator was successfully designed to estimate the key functions in the control system, which avoids the high control gains required to guarantee robustness. I.O. Kadykalo (2021) developed a method of optimising the movement mode of the slewing mechanism of a jib crane during transitional processes, as well as a design of the drive mechanism that allows the implementation of optimal modes of motion the jib crane’s slewing mechanism. Measurements were conducted using an encoder, an analog-to-digital converter, and a frequency converter. Also, the computer program “Optimal control of the jib crane turning mechanism” was developed to implement optimal modes of motion of the slewing mechanism. T.A. Le *et al.* (2013) presented control in the form of feedback for a rotating tower crane, combined with the movement of the trolley based on a

sliding mode. The tower crane's developed motion controllers asymptotically stabilised the system's working state. S. Chwastek (2020) described a method for optimising crane mechanisms to reduce oscillations. The main advantage of the presented method is its simplicity and generality. This study underscores the need for a comprehensive approach to optimising multi-drive systems.

Researches E.Q. Hussein *et al.* (2020) presented the development of a nonlinear controller for the movement of a bridge crane. The procedure for designing the regulator with a sliding mode was detailed. Research showed that sliding mode control (SMC) performs better than a linear quadratic regulator (LQR) and requires less control force. Z. Sun *et al.* (2019) presented a sliding mode controller based on fuzzy logic (FSMC) to solve the problem of eliminating load oscillations that occur during the operation of bridge cranes. Computer simulation showed that FSMC based on the DE algorithm can effectively solve the problem of eliminating pendulum oscillations of the load. In work of S.-J. Kimmerle *et al.* (2018) a mathematical model of the problem of optimal duration movement of the "crane-trolley-load" system was presented. Based on the system's movement model, calculations were conducted to minimise the working cycle for moving load. S.M. Fasih *et al.* (2020) described the method of generating input data for effective control of rotation. The artificial neural network performs the function of suppressing fluctuations of the payload. It is used to develop a form of derivative zero vibration that can be updated according to the length of the rope. Y. Zuo *et al.* (2021) describe a method for quickly obtaining the voltage spectrum and calculating the crane's lifespan. An ANSYS finite element model is created based on static parameters and analyzed to determine the location of the dangerous point. In order to estimate the service life, the method of fracture mechanics is used in the work.

CONCLUSIONS

The problem of synthesising the optimal high-performance acceleration mode for the slewing mechanism of a tower crane has been established. The problem included a mathematical model of the system's motion, boundary conditions (defining the acceleration of the crane to the nominal rotation speed with the elimination of pendulum oscillations of the load), a performance criterion, constraints on the torque, and constraints on the angular velocity of the crane's rotation. Since it was a priori known that the solution to the problem of optimal performance was extreme values of the driving torque, an analytical solution to the system's equations of motion at constant driving torque was found. This allowed us to get derivation for the expressions for the final phase coordinates of the

system's motion and the formation of a nonlinear criterion reflecting the degree of achievement of the final conditions and the duration of the system's movement. The problem of minimising the criterion was solved using the VCT-PSO algorithm with parameters $c_1 = c_2 = 1.19$, $RC = 5$, $w = 0.72$. An artificial neural network was formed to approximate the entire set of solutions to the problem. The neural network had 3 inputs (m, r, l), 3 outputs (t_1, t_2, t_3) and three hidden layers with five neurons each. The network training was conducted using the ADAM method. The root mean square and maximum errors in predicting the duration of the first, second, and third stages of the system's movement were determined (0.34%, 1.08%, 0.41%, respectively), and the maximums (1.44%, 7.34%, 1.63% respectively), indicating the high quality of data approximation. The indicators of the dynamic system's movement under optimal control were least affected by the mass of the load and most significantly by the length of the flexible suspension l . This was due to the strong influence of the value l to the period of the pendulum oscillations. Increasing the value l causes increasing in the duration of optimal control, and, consequently, a more intensive acceleration mode (both, in energy and dynamical senses). The developed approach to solving the problem of optimal control may be considered as a further development in the field of optimal (by duration) control. This contribution gave the general methodology to solve the optimal control problem. It was based on reducing the initial problem, multiple its solution, and training ANN to predict the switching moments of control, according to the parameters of the system to control. That is why the developed methodology may be applied to other dynamic systems (in particular, those corresponding to mechanisms of hoisting machinery: bridge and gantry cranes, lifts, robots, etc.). Future studies in this direction are connected with other parameters accounting. They are related to the mode of the system motion (constraints $M_{\max}$ and $M_{\min}$, rated angular velocity ω), and initial values of the generalised coordinates (first of all θ and $\dot{\theta}$). In addition to that, ANN architecture and the volume of training data – are important issues to study, because of the fact, that they strongly influence the correctness of the switching moments t_1, t_2, t_3 prediction.

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Юрій Ромасевич

Доктор технічних наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0000-0001-5069-5929>

Ярослав Губар

Аспірант
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0009-0000-3651-866X>

Синтез оптимального за швидкодією режиму розгону механізму повороту баштового крана

Анотація. Висока продуктивність вантажопідйомних кранів важлива для зведення будівель і споруд. Одним із ефективних способів цього досягти є усунення маятникових коливань вантажу на гнучкому підвісі баштових кранів. Тому метою статті було отримання загального розв'язку задачі оптимального за швидкодією керування протягом розгону механізму повороту крана. Представлена динамічна модель кранової системи, описані крайові умови, критерій оптимізації та введено обмеження на крутний момент. Виконано зведення вихідної задачі до задачі безумовної оптимізації нелінійної функції. Виконано багатократне розв'язування задачі, в якій маса вантажу m , довжина гнучкого підвісу l та виліт стріли r змінювались у певних межах. Для знаходження розв'язків використаний оптимізаційний алгоритм VCT-PSO. На основі отриманих розв'язків сформовано масив даних для навчання штучної нейронної мережі (навчальна вибірка) та масиву для перевірки її роботи (тестова вибірка). Для задачі прогнозування моментів перемикання керувань використано нейронну мережу прямого поширення із трьома входами (відповідають параметрам m , r , l), трьома виходами (відповідають моментам перемикання керувань) та трьома прихованими шарами з п'ятьма нейронами в кожному. Виконано тренування нейронної мережі за допомогою методу ADAM та визначено результати оцінок якості прогнозу моментів перемикання керувань, представлено графіки похибок оцінок. Встановлено високу якість апроксимації поверхні розв'язків задачі за допомогою штучної нейронної мережі. Проведено аналіз динаміки руху системи при оптимальному керуванні, які показав, що на показники руху системи найменший вплив має маса вантажу m , а найбільший – довжина гнучкого підвісу l .

Ключові слова: баштовий кран; механізм повороту; оптимальне керування; маятникові коливання вантажу; штучна нейронна мережа

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Viktorija Smolij*

Doctor of Technical Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0002-1268-7837>

Natan Smolij

Postgraduate Student
National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute"
03056, 37 Beresteyskiy, Kyiv, Ukraine
<https://orcid.org/0009-0002-3763-6726>

Mykhailo Shvydenko

PhD in Economics, Honoured Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0002-9025-1326>

Semen Voloshyn

PhD in Technical Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0002-4913-7003>

Hardware and software complex for operational management of a flexible site of highly efficient assembly production

Abstract. The work was devoted to the urgent issues of increasing productivity, efficiency and reducing the cost of assembly plants of multi-series productions. The goal of the work was to create an effective hardware and software complex for modelling the process of assembling objects and their components (using the example of power cells), which took into account the structure and parameters of production modules, transport and warehouse systems, allowed generation of initial plans and used Petri nets to determine scenarios for operational management of the specified production process. The distribution of autonomous transport modules by sections of the production site according to a certain structure and number was proposed. The execution time of each operation was calculated, after which a matrix of the duration of detailed operations was created. An initial schedule was drawn up and the decision rules were investigated, and a custom rule was proposed that prioritises details going to the most distant modules. The behaviour of the production system with the resulting schedule was simulated when autonomous transport modules were introduced. The created hardware and software complex, based on a script written in the Python3 language, combined the functionality necessary for the flexible production modules transport service algorithm study, the analysis of the network model for flexible automated production site functioning equipment, and organisation of flexible automated production site operational management subsystems. The obtained modelling results made it possible to adjust site's structural filling and organisation of the

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*Corresponding author



production, transport and warehouse components, eliminating overloading of modules and ensuring a reduction of the industrial cycle while maintaining the volume of work. The Petri net modelling method in the created hardware and software complex made it possible to compare several options for the operational management organisation and to obtain a living grid of a non-accumulating system in which all transitions were activated at least once, and so, obtaining a working option for the effective production process organisation

Keywords: assembly station; robotic production; flexible production modules; technological equipment; automated warehouse; automated transport module

INTRODUCTION

Manufacturing, tuning (stitching), testing, flight tests, sub-tuning of a specific sample for a specific battery to ensure compliance of electrical and tactical-technical parameters with the appropriate values is a very difficult and urgent problem. Solving this challenge ensures accurate, prompt, and effective mission execution and the achievement of the planned results. During a full-scale war in Ukraine, the need for the production of drones is undoubtedly relevant, but equally important are the organisation of flexible robotic production studies, adjusted to ensure the appropriate communication quality parameters, the finished products carrying capacity, reliability, and most importantly, establishing the production rhythm and continuity. At the beginning of the war, the production was voluntary and non-professional, which allowed to gain invaluable experience (although some time and material resources were lost), which confirmed the need of only high-quality components use, unified structural and technological solutions, ensuring quality parameters reproducibility.

According to V. Yakymets *et al.* (2022) the enemy was actively considering the main problems and areas of training highly qualified organisation and production personnel for flexible production and unmanned aircraft and aerial vehicles complexes operations, which will allow him (the enemy) to apply the accumulated knowledge and skills against Ukraine on the battlefield. It was impossible to allow this, so it was necessary to systematise, acquire and introduce new knowledge into development and production technologies for obtaining the highest quality, most effective and optimal UAV samples in terms of tactical, technical and design and technological features.

B. Sopha *et al.* (2024) investigated the problem of staff shortages in the context of the need to increase production through the use of advanced technologies, among other things, the increase in interest in advanced technologies in agriculture and processing, such as IoT, sensors, robots, unmanned aerial vehicles, digitisation and artificial intelligence, which in turn would lead to radical changes in the organisation of production technologies. Considering the subjective component, one should highlight the heuristic nature of each person's decision-making, different financial capabilities and access to commercially available components, different degrees of awareness and skills regarding technological manufacturing processes and their regulatory values, different degrees of ownership for firmware, etc.

Scientists K. Li *et al.* (2022) considered the problems of creating, piloting and organising the operation and use of unmanned systems and complexes. The practice of introducing unmanned aerial vehicles into production and operation was analysed. Problems related to the creation, experimental implementation and organisation of operation and use of unmanned systems and complexes were considered. Organisational and management measures for the sustainable development of the field of unmanned systems for 2023-2030 were proposed.

The option of manually assembling devices from the cheapest components is unacceptable, since there is an extremely low probability of successful, correct and safe performance of the task. Automated production ensured the quality and reliability of finished products while preserving the variation of the required actual nomenclature, the rhythm of production and the required number of finished products.

D. Hawashin *et al.* (2024a) proposed the application of blockchain technology in the industry of unmanned aerial vehicles. Blockchain could provide key solutions to several challenges related to security, data integrity, and operational efficiency in UAV systems. An in-depth study of the transformative role of blockchain in the field of UAVs was conducted. The potential influence and application of blockchain technology for solving problems at the stages of production, planning and operation of UAV systems had been studied.

The proposed hardware and software complex for operational management of the production site provided customisation of product parameters, in particular power elements, for use at certain distances, for work on stationary or moving objects, ensured reproducibility of tactical, technical and operational characteristics. The conjuncture of finished products, coordination of the needs of specific consumers and consideration of feedback on the results of use were taken into account (Perkumienė & Vienažindienė, 2024)

Similar problems were solved by K. Raoufi *et al.* (2024). A scheme of a flexible production cell with placement of mechanical equipment for the manufacture of mechatronic elements of innovative projects was proposed. When creating a flexible production cell in the industrial park of the university, the authors performed scientific research on the planning of technological processes. For functional modelling based on the theory of Petri net graphs, the actions of this object were investigated and a graph-scheme of functional modelling of the machine tool module was

constructed. The addressing parameters in the structure for the implementation of joint management of the network of the researched technological process were defined.

Researchers K. Aghaee *et al.* (2024) developed the most acceptable production methods, covering biological technologies and topology optimisation. The preferred materials and their characteristics for ground, air, and extraterrestrial construction were discussed. In addition, relevant testing methods were presented, and construction-related challenges and limitations were elucidated.

The goal of the work was to create an effective hardware and software complex for modelling the process of assembling objects and their components (for example, power cells), which took into account the structure and parameters of production modules, transport and warehouse systems, allowed generating initial plans and usage of Petri nets to determine scenarios operational management of the specified production process.

MATERIALS AND METHODS

The creation and testing of a hardware and software UAVs components production modelling and operational management complex was an urgent and difficult task, the decomposition of this task involved systematic study of the technological process of assembly and testing of the obtained results. It was impossible to immediately cover all stages and nomenclature of production, therefore, the production of batteries for unmanned aerial vehicles was studied deeply compared to other parts of technological process. To ensure the products supply to the flexible production module and the interaction organisation with the automated system in the flexible automated section, an automated transport system was used as part of transport modules or stacker robots that had transport routes

of movement. These routes were circular (closed one-way traffic), linear (bidirectional open traffic) or mixed (combination of linear and circular routes). With high loading of the flexible production module, the use of input and output drives was mandatory. The choice of the specified layout solution for the scheme of the production area allowed to divide and speed up the transport process service by replacing the first operation of transporting with the next part for processing, and then the transportation of the previous one, which was already expected for further processing already on another flexible production module.

The load estimate of a flexible production module was considered to be the ratio of the number of parts processed by the specified module to the nomenclature number of parts. If the value was no more than 0.3, then one drive was enough. There were also some restrictions imposed on the operation of storage devices and the operation of the flexible production module, which were related to ensuring the requirements for the procedure for initiating a technological operation on the equipment. In particular, the following was considered: the automatic transport module couldn't bring the next part to the flexible production module for processing while its input storage was loaded; the flexible production module couldn't start processing the loaded part from the input drive while its output drive was occupied; after completion of processing on the flexible production module, the part immediately arrived at its output storage.

For the construction of the specified hardware and software complex, a number of initial conditions were considered, in particular, that 14 parts were processed with the following nomenclature of operations performed on each of them. Groups of operations for the manufacture of parts are presented in Table 1.

Table 1. Nomenclature of parts and list of operations

Nº	Marking	Order of operations
1	0	T1,T2,C1,F2,F3
2	1	T5,T4,T1,C2,T3
3	2	T2,C1,C2,F1,F2,P2
4	3	T1,T2,C1,T3,C2,T4,F1
5	4	T3,T4,C2,F1,P1,T3,T5
6	5	T2,C3,F1,T3
7	6	T1,T2,C1,P2,F1,T3,T4
8	7	T4, T2, C3, C2, F1, F2, T5
9	8	T1, T4, T2, C3, T5
10	9	T1, C1, T4, T2, C1, F2, T5, F1
11	10	T4, T2, C3, F2, T5
12	11	T3, T4, T2, C3, C2, F1
13	12	T3, C1, T4, T2, C3, T5
14	13	T4, T2, C3, T1, C1, T5

Note: Ti, Ci, Fi, Pi – varieties of types of investigated operations

Source: compiled by the authors

The time components and the average speed of movement of components in a flexible automated section, which

was used for the calculation of design problems, are given in Table 2.

Table 2. The main parameters of the functioning of a flexible automated precinct

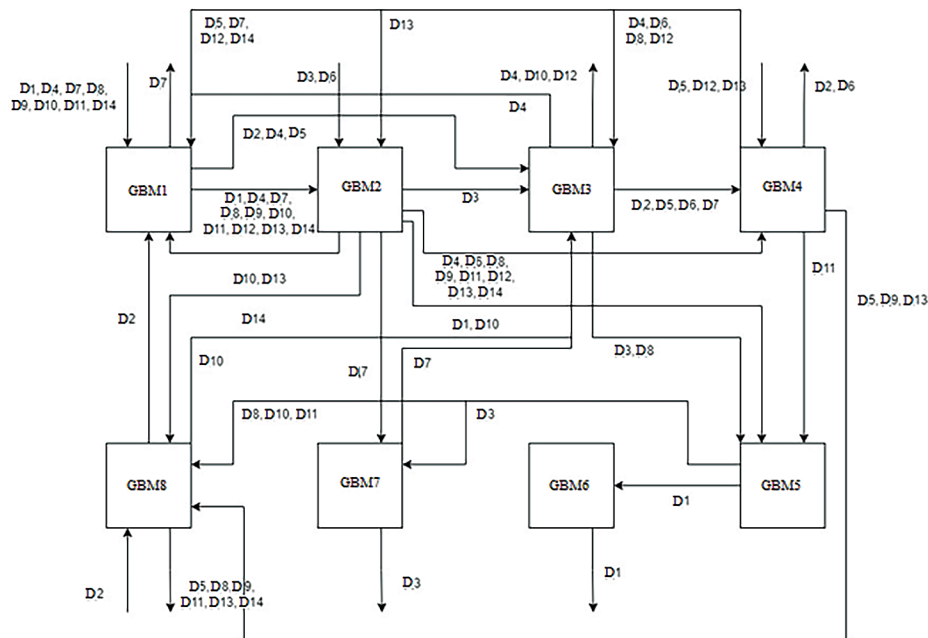
Parameter	Marking	Unit of measurement	Value
The average processing time of one detail installation	t_{OB}	hour	0.3
The loading time of the flexible manufacturing module	t_Z	minute	6
The unloading time of the flexible production module	t_p	minute	6
The average length of movement of the stacker robot	l_{CP}	meter	40
The average speed of movement of the stacker robot	v_{CP}	meter / minute	30
Time for the take/put operation	$t_{VZ/POC}$	minute	0.21

Note: there is a very large range of parameter values

Source: compiled by the authors

The Figure 1 shows parts movement graph between working equipment. GBM1 and GBM2 served the largest number of product nomenclature, GBM6 served the

smallest number, which was due to the specialisation of performed functions, transformations and operations and features of the blank processing process.

**Figure 1.** Graph of technological operations

Note: GBM1...8 – flexible production modules, D1...14 – details

Source: compiled by the authors

The flexible automated site included eight flexible production modules, for each of them the following module specialisation was involved: M0: {T1, T4}; M1: {T2, C1}; M2: {C2, F1, P1}; M3: {C3, T3}; M4: {F2}; M5: {F3}; M6: {P2}; M7: {T5}. Petri nets were used as a modelling method in the created hardware and software complex of the experimental production site, which allowed comparison between several options for their organisation and operational management. The proposed hardware and software modelling complex was written in the Python programming language version 3.10.4 with the usage of the following libraries: Numpy – for organising large volumes of calculations; Matplotlib – for visualisation of Gantt charts; Xlwt – for recording data about transitions in an Excel file; Pygame – for visualisation of the constructed Petri net.

RESULTS AND DISCUSSION

The creation of highly efficient assembly production was particularly acutely dependent on the assembly unit's manufacturability. The assembly itself was the main criterion that determined the quality of design developments for specific production conditions. The indisputable trend of modern production is the formation of certain flexible production systems, which includes automated departments, designed for appropriate productivity and assembly volumes. The research carried out in the work is relevant, in particular, when launching, debugging and testing such productions as battery accumulators for unmanned aerial vehicles. The specified complex included relevant technological equipment, in particular, a battery life cycle tester, battery and cell testing equipment, a battery marking

machine, a battery cell sorting machine, a cylindrical battery visual inspection machine, battery spot welding machine, test equipment, integrated battery tester, battery aging machine, battery assembly equipment, battery module stacking and pressing machine, etc. (Fig. 2).

The specified production should be integrated with the production of drones of a certain type and variety, which in turn includes equipment for the manufacture of cases, large-node assembly of electronic components,

corresponding varieties and types of batteries, etc. Special attention was required for the so-called “software component” in setting up the device. It was necessary to agree with the manual execution of certain technological processes, and the quality control system with rejection and to ensure the possibility of prompt replacement of the nomenclature of products depending on the available ones, replacement of components, variation of manufacturing parameters, etc.



Figure 2. Technological equipment for battery production

Note: numbers indicate the sequence of actions in accordance with route maps of technological routes

Source: stage of assembling a power element from open sources of information

The structural and technological diagram of a flexible automated station equipped with the appropriate number of production modules and operations performed on each module, is shown in Figure 2. Separately marked streams of parts that were processed by the corresponding technological module.

After calculating the load factors of each module to determine the number of drives, 11 pieces of autonomous transport modules were obtained that were needed to move production objects between the warehouse and production modules. As a result, the structural and composition scheme of the flexible automated section was taken on the form shown in Figure 3. Here was defined transport schemes (routes) of transportation of processed parts on flexible production modules and between them, and schemes of their interaction with the automated warehouse. The type of chosen transport system of the flexible automated section was a combined circular-linear type.

In the proposed structural and composition scheme of the flexible automated section, an automated warehouse

with five transshipment points (overloading) was provided, which acted as a central warehouse for intermediate storage of production facilities before switching to flexible production modules or for final storage of finished products. The functions of overload points were not divided into input and output. To draw up a schedule for the technological equipment operations while solving the problem of operational planning for a flexible automated station, it was necessary to determine a technological route for each part, which included the order of its passage through the technological equipment of a flexible automated station and the processing time of each unit of equipment. To calculate the technological route, it was necessary to determine the nomenclature of parts, the sequence of the processing stages and the processing equipment. The technological route included the order of passage of parts through the technological equipment (part installations) and the time of processing the part on a unit of technological equipment. The order of passage of parts through the technological equipment was determined according to the list of

operations (detail operations) that had been carried out for the production of parts, and based on the operational

module's specialisation (Fig. 3). The corresponding matrix of detailed operations is given in Table 3.

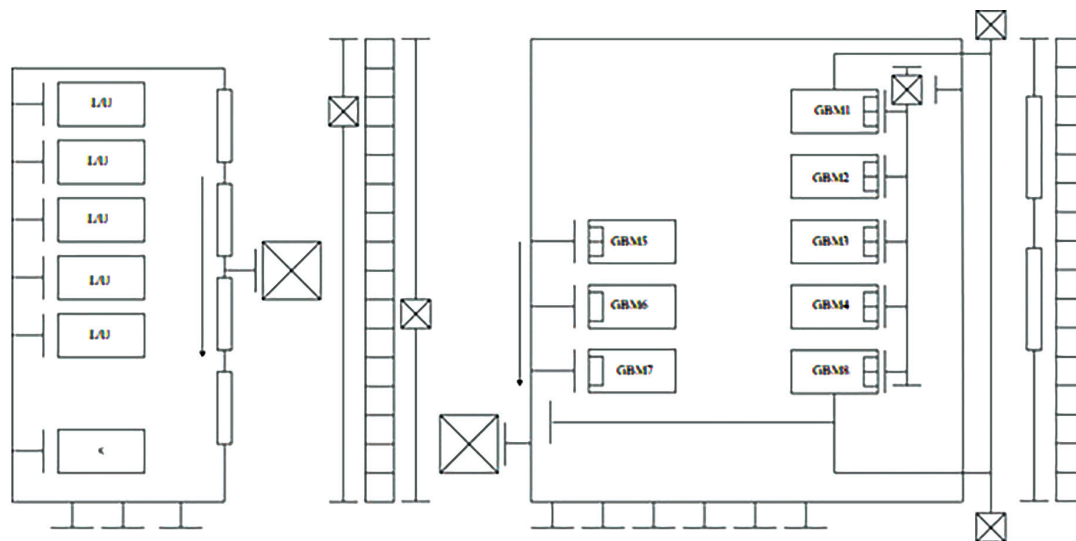


Figure 3. Structural and composition scheme of a flexible automated section

Note: L/U – loading/unloading, K – compiler, GBM1...8 – flexible production modules

Source: compiled by the authors

Table 3. Matrix of detailed operations

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14
DO1	T1 M1	T5 M8	T2 M2	T1 M1	T3 M4	T2 M2	T1 M1	T4 M1	T1 M1	T1 M1	T4 M1	T3 M4	T3 M4	T4 M1
DO2	T2 M2	T4 M1	C1 M2	T2 M2	T4 M1	C3 M4	T2 M2	T2 M2	T4 M1	C1 M2	T2 M2	T4 M1	C1 M2	T2 M2
DO3	C1 M2	T1 M1	C2 M3	C1 M2	C2 M3	F1 M3	C1 M2	C3 M4	T2 M2	T4 M1	C3 M4	T2 M2	T4 M1	C3 M4
DO4	F2 M5	C2 M3	F1 M3	T3 M4	F1 M3	T3 M4	P2 M7	C2 M3	C3 M4	T2 M2	F2 M5	C3 M4	T2 M2	T1 M1
DO5	F3 M6	T3 M4	F2 M5	C2 M3	P1 M3		F1 M3	F1 M3	T5 M8	C1 M2	T5 M8	C2 M3	C3 M4	C1 M2
DO6			P2 M7	T4 M1	T3 M4		T3 M4	F2 M5		F2 M5		F1 M3	T5 M8	T5 M8
DO7				F1 M3	T5 M8		T4 M1	T5 M8		T5 M8				
DO8										F1 M3				

Note: parts passage order through technological equipment is taken into account

Source: compiled by the authors

After transforming the matrix of detail operations by combining related operations into one stage of detail processing on one flexible production module, a corresponding matrix of technological routes was obtained as an execution sequence of detail installations. The execution time of each operation depended on its complexity, which determined a part of the total duration of all operations. The complexity of the operation was established according to the order of their application in the matrix of detailed operations, based on the following: the closer the operation application was to the beginning of the technological process (sequence), the more difficult it was considered to

be in terms of time spent; the preferred place (position) of the application of the operation was considered to be the place where it occurred for most part routes.

From the matrix of detailed operations, a technological process operations use matrix was obtained, with the calculation of the number of uses of operations at each of the positions where they occurred. The time for each operation was calculated based on the following formula:

$$t_i = k_i * t^{max}, \quad (1)$$

where k_i – operation complexity factor.

Value t^{max} defined as:

$$t^{max} = \frac{m_{ds} * t_{pt}}{\sum_i k_i * m_i}, \quad (2)$$

where m_{ds} – number of detail settings; t_{pt} – processing time (0.3 h); k_i – the complexity factor of the i -th

operation; m_i – number of applications of the i -th operation, $\sum_i k_i * m_i = 6.61482683982684$. In accordance: $t^{max} = 8 * 0.3 / 6.615 = 0.362811 \text{ h} = 21.769 \text{ min}$.

Hence, the complexity and time of the corresponding operation form the matrix of the durations of processing parts, which is given in Table 4.

Table 1. Matrix of durations of processing parts

	D1	D2	D3	D4	D5	D6	D7	D8	D9	D10	D11	D12	D13	D14
DU1	8.708	15.238	34.83	8.708	17.415	21.769	8.708	19.592	28.3	8.708	19.592	17.415	17.415	19.592
DU 2	34.83	28.3	16.327	34.83	19.592	6.531	34.83	21.769	21.769	13.061	21.769	19.592	13.061	21.769
DU 3	4.354	5.442	4.354	17.415	17.415	10.885	3.265	6.531	6.531	19.592	6.531	21.769	19.592	6.531
DU 4	2.177	17.415	3.265	5.422	17.415	17.415	10.885	16.327	15.238	34.83	4.354	6.531	21.769	8.708
DU 5				19.592	15.236		17.415	4.354		4.354	15.238	16.327	6.531	13.061
DU 6				10.885			19.592	15.238		15.238			15.238	15.238
DU 7										10.885				
DU 8														
Sum	50.069	66.395	58.776	96.872	87.075	56.6	94.965	83.811	71.838	106.668	67.484	81.634	93.606	84.899

Note: duration is measured in minutes

Source: compiled by the authors

Possible movements with distances in conventional units were studied, movement time was calculated without taking into account additional operations, allowances for transportation time were calculated, based on the formulas for movement maintenance:

for transition PP – GBM:

$$t_{obsl} = t_{vz} + t_{tp} + t_{post} + t_z, \quad (3)$$

for transition GBM – PP:

$$t_{obsl} = t_p + t_{vz} + t_{tp} + t_{post}, \quad (4)$$

for transition AC – PP:

$$t_{obsl} = t_{vz} + t_{tp} + t_{post}, \quad (5)$$

for transition PP- AC:

$$t_{obsl} = t_{vz} + t_{tp} + t_{post}. \quad (6)$$

for transition AC-GBM:

$$t_{obsl} = t_{vz} + t_{tp} + t_{post} + t_z, \quad (7)$$

for transition GBM-AC:

$$t_{obsl} = t_p + t_{vz} + t_{tp} + t_{post}, \quad (8)$$

for transition GBM-GBM:

$$t_{obsl} = t_p + t_{vz} + t_{tp} + t_{post} + t_z, \quad (9)$$

where t_{obsl} – service time, t_{vz} – time to take (capture) the detail, t_{tp} – moving time, t_{post} – time to place (drop) the detail, t_z – loading time, t_p – unloading time.

The planning process included jobs, which were technological operations performed on batches of parts. The main purpose of planning was to determine the order and time of passage of parts through the equipment, taking into account fixed technological processing routes. The technological route provided for the sequence of technological operations on the equipment, but did not determine

the specific terms of receipt of parts. Technological routes could be both sequential and cyclical or different for all processed parts or have partial similarity.

Nomenclature list of products produced on m groups of equipment ($k = 1, \bar{m}$), consisted of n names of details ($j = 1, \bar{n}$). The production of a batch of parts of each denomination was determined in advance by the sequence of passage of parts through groups of equipment, which was called a technological route:

$$G_j = (Lij | i = 1, \bar{Mj}), \quad (10)$$

where Lij – technological operation, which is performed i -th in the order of production of the j -th part; Mj – number of operations performed on the j -th part. Technological operations were on the route $Lij = (Qij, Tij)$ had the following characteristics: $Qij = k$ – the number of the equipment group configured to perform the operation Lij ; Tij – regulatory duration of the operation Lij .

It was necessary to make a schedule $P = (Tij\pi | i = 1, Mj, j = 1, n)$, which determined the start of operations Lij (starting moments of a batch of parts on equipment units) and satisfied the system of constraints: the condition of execution of the technological sequence $Tij\pi \geq Ti - 1, jK$; under the conditions of execution of technological routes Gj ; provided operations were performed without interruptions $TijK = Tij\pi + Tij$; provided that only one operation per unit of equipment was performed at each moment of time $\forall Li1j1, Li2j2: (Qi1j1 = Qi2j2) \rightarrow (Ti1j1K \leq Ti2j2\pi) \cup (Ti2j2K \leq Ti1j1\pi)$, where $TijK$ – operation completion moment Lij .

In operational and dispatch management, important indicators of the quality of implementation of the formed schedule were the reliability of execution under external influences. These metrics included factors such as equipment downtime, waiting time for parts to be processed, and local time reserves.

For decision rules in simulation modelling algorithms, different preference rules were used. Obviously, there was a possibility of situations where the use of only one rule did not provide an unambiguous sequence of starting parts. To achieve unambiguity, an additional rule was used that allowed to choose one alternative from the set of options that were selected according to the first rule. One of the possible additional rules was determining the order by part number. For example, if the part number was the smallest,

then it was processed first, which ensured an unambiguous start sequence. The following rules were chosen to schedule the technological equipment work: maximising residual labour intensity, prioritising spare parts that travelled the furthest distance from the automated warehouse (a rule proposed by the authors), and the longest-operation rule. Having determined the order of passage of modules for the manufacture of each part, the corresponding time matrix of the duration of detail operations was formed (Table 5).

Table 5. Matrix of durations of processing parts

Manufacture path of every detail		Detail operations duration matrices
D0	[0, 1, 4, 5]	[8.708, 34.83, 4.354, 2.177]
D1	[7, 0, 2, 3]	[15.238, 28.299999999999997, 5.442, 17.415]
D2	[1, 2, 4, 6]	[34.83, 16.326999999999998, 4.354, 3.265]
D3	[0, 1, 3, 2, 0, 2]	[8.708, 34.83, 17.415, 5.442, 19.592, 10.885]
D4	[3, 0, 2, 3, 7]	[17.415, 19.592, 17.415, 17.415, 15.238]
D5	[1, 3, 2, 3]	[21.769, 6.531, 10.885, 17.415]
D6	[0, 1, 6, 2, 3, 0]	[8.708, 34.83, 3.265, 10.885, 17.415, 19.592]
D7	[0, 1, 3, 2, 4, 7]	[19.592, 21.769, 6.531, 16.326999999999998, 4.354, 15.238]
D8	[0, 1, 3, 7]	[28.299999999999997, 21.769, 6.531, 15.238]
D9	[0, 1, 0, 1, 4, 7, 2]	[8.708, 13.061, 19.592, 34.83, 4.354, 15.238, 10.885]
D10	[0, 1, 3, 4, 7]	[19.592, 21.769, 6.531, 4.354, 15.238]
D11	[3, 0, 1, 3, 2]	[17.415, 19.592, 21.769, 6.531, 16.326999999999998]
D12	[3, 1, 0, 1, 3, 7]	[17.415, 13.061, 19.592, 21.769, 6.531, 15.238]
D13	[0, 1, 3, 0, 1, 7]	[19.592, 21.769, 6.531, 8.708, 13.061, 15.238]

Note: duration is measured in minutes

Source: compiled by the authors

As it was mentioned above, the main rule of preference was the rule of maximum residual labour intensity, since the average production time of each part was 78.602 min. Below this value, 6 details and for 8 – above. Accordingly, the rule of maximum residual labour intensity was considered as the one to reduce the production time of a larger number of parts.

The use of an auxiliary rule reduced the load on the first modules, since a higher priority during processing gave to parts whose next operation was performed on a machine with a higher serial number.

Also, in order to solve all possible conflicts that could arise when applying these rules, it was advisable to use the LPT priority rule, as this would help to advance the parts to the most distant machines, since there were mainly short-time operations. Simulation results were given for a combined rule with a sequence of application MWKR – FPD – LPT. The class diagram is shown in Figure 4.

File main.py consists of 4 main components:

1. Class `task_manager` that constructed an initial ideal schedule based on given rules with prioritisation according to the submission sequence. The resulting sequence of detail processing was transferred to the `time_table_extender` class using the `form_periods()` method. The class constructor accepted the following arguments: a matrix of transitions through part modules, a matrix of part processing time at each stage, the number of parts for processing, the number of processing modules, all possible priority rules were implemented.

2. Class `time_table_extender` that performed schedule extension and data generation for the Petri Net construction phase. The class constructor accepted the following arguments in the appropriate sequence: the matrix of transitions through modules of parts, the matrix of the cost of transitions between modules, the matrix of the time of processing parts at each of the stages, the sequence of processing parts for each flexible production module, the number in which the automated warehouse stands in the matrix of movements (starting with 0), the number in which there was an overload point in the movement matrix (if there wasn't, it was necessary to provide the total number of flexible production modules + 1), an array characterising the number of modules in each part of the flexible automated site, an array characterising storage units (input storage capacity, output storage capacity, or the total capacity if the drive works in both input and output mode).

3. The field of entering input data included: `Ops` – a list of operations that can be performed, `Input_array` – encrypted with elements from the previous array of the technological process of processing parts, `timings` – the duration of each operation, `modules` – a description of the modules with the operations they perform, `moves_price` – a matrix characterising the cost movements in the system of a flexible automated precinct (0 means there was no movement). Customising the script to work with each individual system was done by changing the values of these data arrays.

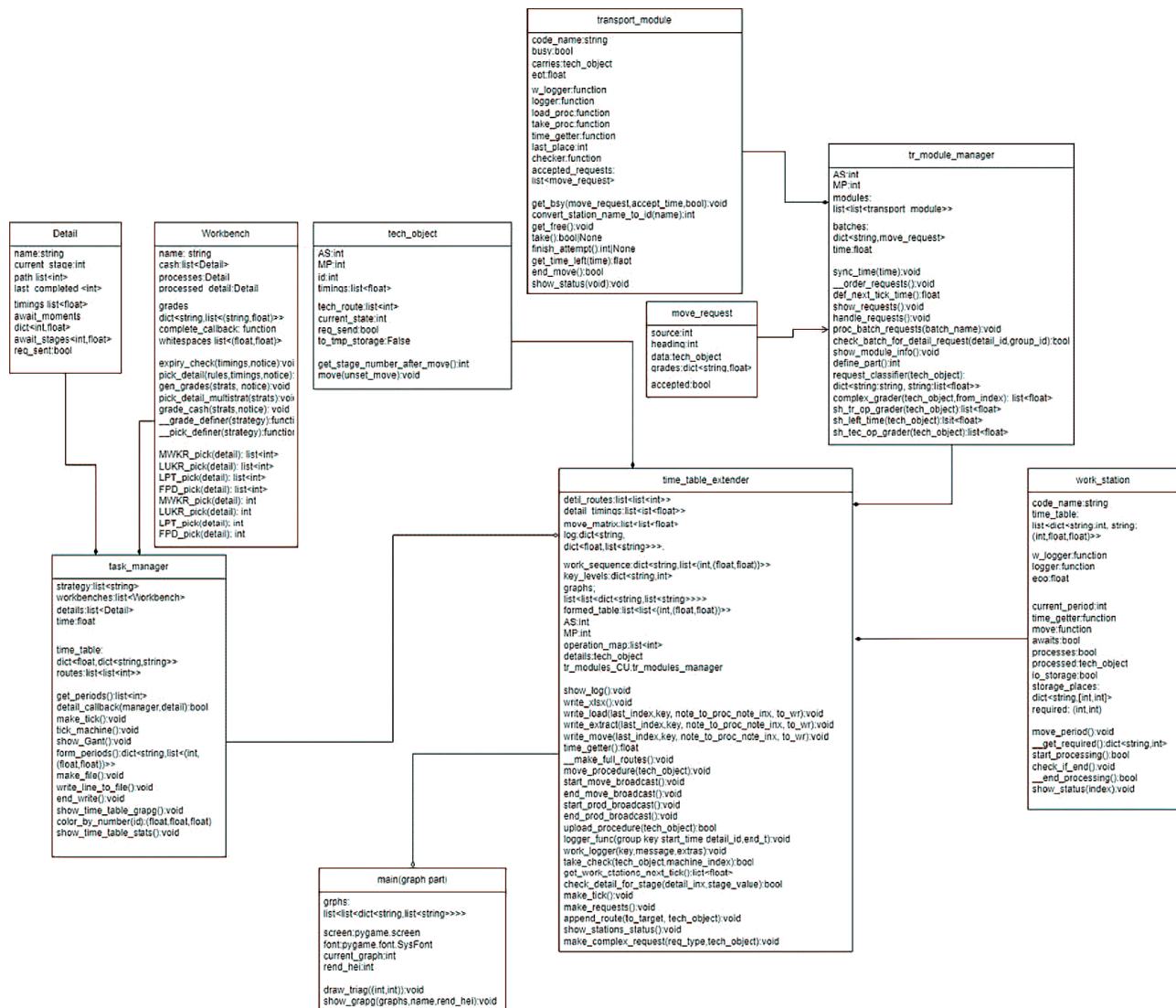


Figure 4. Class diagram

Note: all components of the automated production process are presented

Source: compiled by the authors

4. Petri net visualisation was implemented with pygame tools, when the nets were built for each module separately. The module displayed was selected by keys 1 and 2, the scheme was scrolled by the up and down arrow keys.

The created hardware and software complex sequentially outputted a Gantt chart for the primary schedule, then a similar chart for the extended schedule. After analysing and closing the contents of these windows, a window appeared with the results of modelling the specified production process using Petri nets. Also, in the process of generating the schedule, logs appeared in the console for each important moment in time (screening), in which it was possible to see the description of the system in this time period, active requests and their evaluations according to various criteria. After the extended schedule was generated, the petry.xls file containing descriptions of transitions

in the Petri net appeared in the file folder. The simulation results are shown in Figure 5. The analysis of the structural and compositional scheme showed that the application of a ring unidirectional transport service scheme of all flexible production modules and an automated warehouse with the help of two automated transport modules was the most rational and effective. This proved a concept that if there was an application from flexible production modules or an automated warehouse, it must be served by the nearest free transport module. This principle appeared to be the most optimal, because the least possible time would be spent on transportation at the moment. The result of the dispatch control algorithm based on the transport service strategy was an extended Gantt chart (Fig. 6), in which all units of technological and transport equipment were reproduced, all processing and maintenance operations were coordinated.

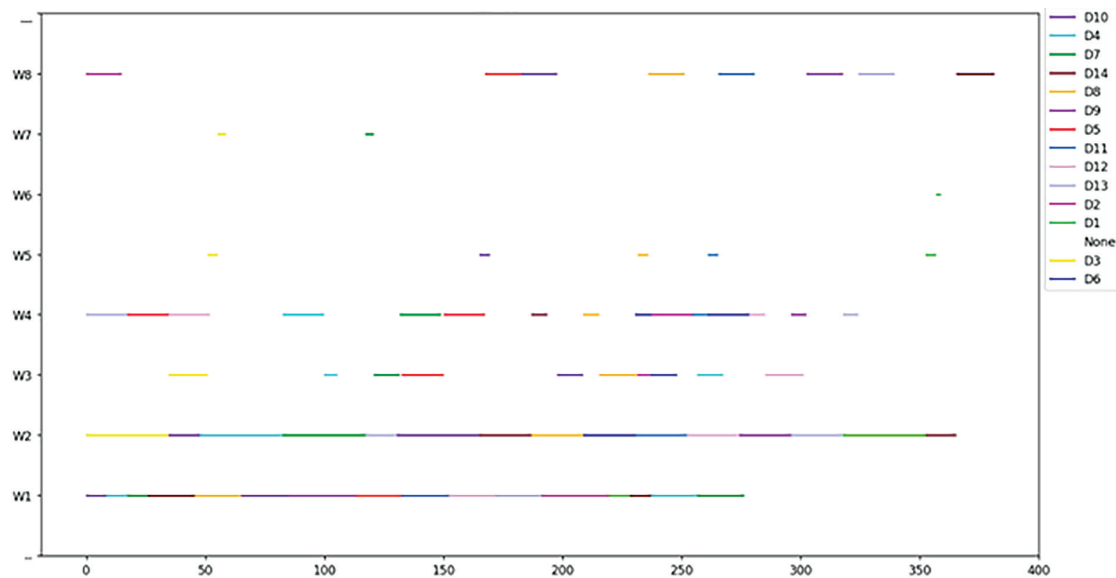


Figure 5. Simulation results

Note: corresponding colors indicate the Gantt Charts for the corresponding details

Source: compiled by the authors



Figure 6. Extended schedule of operation of technological equipment (system simulation results based on input data)

Note: in the diagram, the machine tools have a name with a single number starting with 0

Source: compiled by the authors

As a result of the simulation, a certain sequence of processing parts was obtained that satisfied the conditions of the assembly technological process. An effective tool for analysing the state of loading of automated production components was obtained. In particular, in Figure 5 shows an extended schedule of the technological equipment, the obtained sequence of processing parts by autonomous transport modules such as:

0/0:[9]

0/1:[1]

0/2:[12]

0/3:[2]

0/4:[3]

0/5:[9, 6, 13, 7, 12, 4, 2, 9, 2, 2, 8, 11, 11, 6, 7, 11, 11, 5, 7, 5, 4, 4, 1, 7, 3, 9, 9, 13, 1, 5, 10, 8]...

The sequence of processing parts by flexible production modules looks like this:

0:[9, 3, 6, 13, 7, 9, 8, 4, 10, 11, 12, 1, 0, 13, 3, 6]

1:[2, 9, 3, 6, 12, 9, 13, 7, 5, 10, 11, 8, 12, 0, 13]

2:[2, 3, 6, 4, 9, 7, 1, 5, 3, 11]

3:[12, 4, 11, 3, 6, 4, 13, 7, 5, 1, 10, 5, 11, 8, 12]

4:[2, 9, 7, 10, 0]

5:[0]

6:[2, 6]

7:[1, 4, 9, 7, 10, 8, 12, 13]

According to the simulation results, the total order processing time increased from 380,954 min to 1143.228 min. Since the modelling process considered modules that have an input drive, a work area, and an output drive of variable capacity, the production processes were described as follows. For each part there were following positions:

$D\{N^0\}_{\text{stage}}_A$ – detail in the automated warehouse before the stage.

$D\{N^0\}_{\text{stage}}_P$ – in the overload device to the stage (if there were 4 stages in the processing of the part, such as in part 0, then after the completion of 4 stages, the 5th stage of transfer to GBM).

For each stage of detail processing:

$D\{N^0\}_{\text{stage}}_I$ – in the input drive for stage processing stage.

$D\{N^0\}_{\text{stage}}_W$ – undergoing stage processing stage.

$D\{N^0\}_{\text{stage}}_O$ – in the source drive is ready for further processing at the stage.

The following positions were introduced for flexible production modules:

$P\{N^0\}_{\text{iteration}}$ – module needs details from an iteration of its workflow N^0 iteration.

There was a number of positions for iterating through the stages of ATM operation:

$A\{N^0\}_{\text{iteration}}$ – module needs details from an iteration of its workflow N^0 iteration.

Also, for convenience, the position $T0_F$ was entered, that marked the presence of the part in the overload point. Next, the transitions for each process were described in detail, in particular, the process of loading into the workspace from the input drive had the form given in Table 6.

Table 6. Formalisation of the process of loading into the workspace from the input drive

Position	Description	Entry/Exit	Inhibitor
$D\{N^0\}_{\text{stage}}_I$	Detail in the input drive	Entry	
$P\{N^0\}_{\text{iteration}}$	The flexible production module is in a stage that allows you to accept this part	Entry	
$D\{N^0\}_{\text{stage}}_W$	Detail in the workspace of the flexible production module	Exit	
$D\{N^0\}_{\text{stage}}_W$	The part from the previous iteration is in processing state		Inhibitor

Note: proposed notation of equipment states for working automata: Entry, Exit, Inhibitor

Source: compiled by the authors

The formalisations specified in Table 6 were carried out for the processes of loading into the output storage from the work area, for transportation from the automated warehouse, from the transshipment point, from flexible production modules, input positions for transportation from flexible production modules to the automated warehouse, to the transshipment point, to flexible production modules.

Each of the elements of the experimental structure of the manufacturing process was simulated by the developed hardware and software complex. In particular, the Petri net for flexible production module 0 has the form shown in Figure 7.

Initial markings (listed positions in which markers were present) followed next naming rules:

➤ all parts are in an automated warehouse: $D0_A, D0_A, D1_A, D2_A, D3_A, D4_A, D5_A, D6_A, D7_A, D8_A, D9_A, D10_A, D11_A, D12_A, D13_A$;

➤ all flexible manufacturing modules on the 1st iteration of the work cycle: $P0_1, P1_1, P2_1, P3_1, P4_1, P5_1, P6_1, P7_1$;

➤ all automated transport modules are on the 1st iteration of the work cycle: $A0/0_0, A0/1_0, A0/2_0, A0/3_0, A0/4_0, A0/5_0, A0/6_0, A0/7_0, A0/8_0, A1/0_0$.

An oriented view of the corresponding set of transitions for the modeled system is given in Table 7.

Table 7. Multiple transitions

Module	Transition	Position	Description of the performance condition	Condition type	Note
				Entry/Exit	Inhibitor
GBM 0	$T0/9 1P$	$D9_1_I$	Detail 9 in the input storage of GBM 0 before stage 1	Entry	
		$P0_1$	GBM 0 waiting for detail 9 before stage 1	Entry	
		$D9_1_W$	Detail 9 in the work area undergoes processing at the stage 1	exit	
		$D6_6_W$	Detail 6 GBM before step 6 in the input drive 0		Inhibitor
...	...	...	...	...	...

Note: simulation results of the specified type were obtained using the proposed hardware and software complex for all production components

Source: compiled by the authors

Module:0

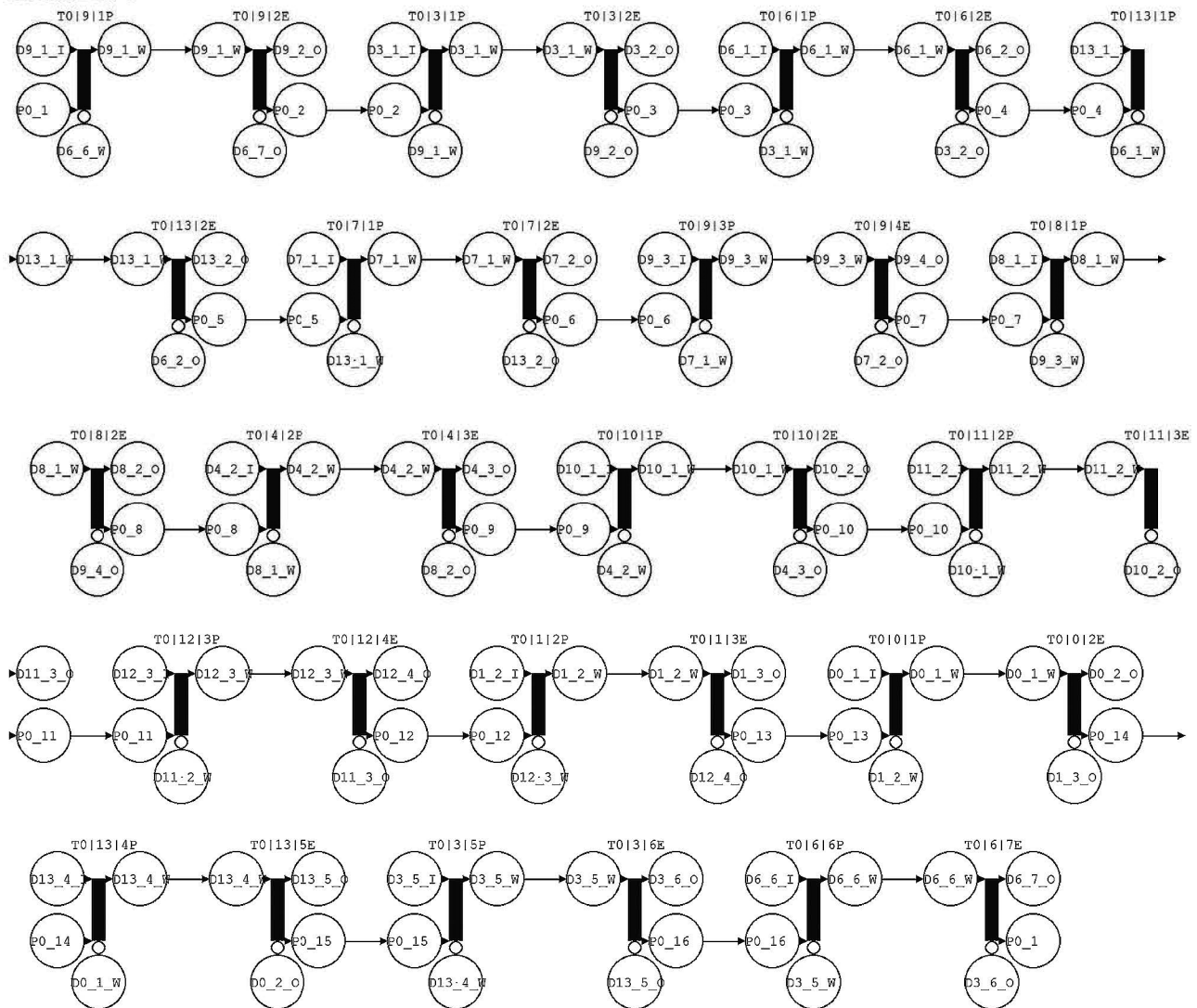


Figure 7. Multiple transitions

Note: D – details, T – time, P – stage in the operation of the equipment

Source: compiled by the authors

There were no loops in the work of this model, all transitions worked. Flexible production modules and automated transport modules, after completing the assigned tasks, were again in a state of readiness to work with the first parts according to their schedule, but the Petri net was not alive because the part after processing at the last stage was into the state of the finished part.

The obtained grid was limited because there were no accumulative markings, thanks to which the finiteness of the processes was ensured. N. Feng *et al.* (2024) demonstrated the effectiveness and usability of the proposed software design approach for the analysis and debugging of 233 N-NFRs related to 62 software-related problems in robotic systems, including robot aids and drones used in the production of robots and their subsystems. R. Ghimire *et al.* (2024) proposed a new approach for using

machine learning in the design, development, and testing of multifunctional composites for aircraft, unmanned aerial systems, and spacecraft. The architecture of an artificial neural network was proposed in this work. The approach integrates the complete life cycle of devices. The proposed method uses the power of ANNs on metadata to characterise multifunctional properties of materials and processes, as well as display failure modes against predicted models and history.

The work of A. Koganti *et al.* (2024) was devoted to the improvement of electronic devices. By analogy with this work, in the research carried out by the authors, the emphasis was on creating a simulation model for the manufacture of drone components in software, where the performance of each technological module was determined and the continuity of the entire production was ensured. The

issue of layout of technological areas was systematically solved for the reproducibility of technological parameters and ensuring the efficiency of drone production.

P. Raj *et al.* (2024) analysed digitisation and digitisation technologies. All industrial artifacts were digitised, connected, and able to be cognitive in their operations, offerings, and products. Through smart use of an amazing array of digital technologies and tools, interaction and collaboration with human experts. Such cognitive industrial machines, equipment, devices, assembly lines, robots, vehicles, drones and other assets together provide an intelligent environment for the development and implementation of cutting-edge industry 4.0 and 5.0 applications. Every industrial process was optimised and automated to produce next-generation products to satisfy consumers, explore new ways to increase revenue and improve productivity. In addition, there were chapters that illustrate industrial use cases, infrastructure optimisation, technology adoption, and AI-powered data analytics for industrial automation. The specified approaches and trends were generalised and adapted to solve the specific task of building a hardware and software complex for operational management of an operational production site. The technologies of using artificial intelligence have not yet been considered due to the limited time requirements for solving the given task, which may be eliminated in future research.

E. Karadag *et al.* (2024) the design process was studied with load options at each point of the motor, so that the result of the drone has an optimal design, light and strong. Combined with 3D printing, complex geometries can be created and material waste can be reduced. Variants of the design of the device with minimal production costs were analysed, which was aimed at effective use of materials and ensuring the best tactical and technical indicators for unit production. The problem of optimisation of large-scale multi-item production was only mentioned in the future.

B. Zhou *et al.* (2024) analysed the production of aviation equipment (e.g., ballistic missiles, missiles, unmanned aerial vehicles (UAVs) and aircraft) and concluded that traditional assembly quality inspection methods mainly rely on manual control of laser trackers with one or more stations, but they were unable to measure and evaluate complex components of aviation equipment. This document presents a method of automatic detection and assessment of assembly accuracy, where at each measuring station the robot controls the movement of the scanning arm; after the completion of all measurement processes, data from several measuring stations were integrated into one coordinate system for calculation and analysis of assembly quality.

J. Ren & Q. Quan (2024) solved the problem of managing the docking station during the refuelling stage, which requires a high level of safety, accuracy and efficiency. As a result, the modelling and control problems that arise in the refuelling phase were typical and complex. First, the article presents the fundamental idea of management, after which the characteristics and requirements for management were

outlined. Advances in modelling and control techniques were then systematically reviewed.

By the authors D. Hawashin *et al.* (2024b) proposed a blockchain and non-fungible token (NFT) based solution that manages, certifies and tracks the origin, history and ownership of UAVs and their production components. The solution provides decentralisation, transparency, visibility and reliability. Complex NFTs were used that collect and store UAV data in a hierarchical structure where parent NFTs represent collected UAV data and child NFTs represent individual parts of the UAV. This approach ensures traceability in the system and facilitates the smooth exchange of ownership rights.

Q. Wang (2024) described the surge in attempts to build homemade UAVs and the challenges in implementing control systems that can effectively control multidimensional UAV operations, especially in the context of proportional-integral-derivative (PID) control. Investigated the choice of PID control configuration to achieve optimal UAV performance. Summarised the most acceptable management model. Using tools such as MATLAB, the various roles and effects of each parameter in the field of PID control were explored, thus providing valuable perspectives for hobbyists and professionals involved in the field of UAV design and control mechanisms.

G.P. Badea *et al.* (2024) created an innovative unmanned aerial vehicle designed for a specific mission. The main objective of this research was to develop an innovative hybrid UAV concept with key features including a fixed-wing design and integrated vertical take-off and landing capability in an experimental model. This document details the entire drone manufacturing and assembly process, covering both the structural framework and associated electrical installations.

M. Battaglia *et al.* (2024) proposed innovative approach to design and manufacture the UAV tail using additive manufacturing completely changes the concept of designing and manufacturing products using traditional methods. AM-based processes can reduce costs, lead times, and increase design freedom by allowing parts to be tailored to specific needs. A key advantage of AM processes was the ability to create optimised structures with reduced mass and without compromising structural efficiency. This was made possible by the combination of high-performance AM materials and the extraordinary manufacturing capabilities of AM technologies, combined with an appropriate design approach for additive manufacturing that overcomes traditional manufacturing techniques.

In the works V. Smolij *et al.* (2023) the general issues of management of complex technological objects with the provision of optimal parameters of the course of technological processes were investigated, and in works V. Smolij *et al.* (2024) directly robotic links of production sites were investigated, software tools for modelling components and processes were tested, connections between the parameters of finished products and the organisation of the production process were analysed in detail.

In current research a distribution of autonomous transport modules across sections of the production site according to a specific structure and quantity was proposed with an example for the technological assembly process (using the example of battery production for unmanned aerial vehicles). As a result of the processing data for technological processes through math computations and variety of simulations, the execution time for each operation was determined, which allowed for the creation of a matrix of the duration of individual operations. Based on this data, an initial schedule was drawn up, where decision-making rules were investigated, including a custom rule prioritising parts destined for the most distant modules.

CONCLUSIONS

For the technological assembly process (using the example of battery production for unmanned aerial vehicles), a distribution of autonomous transport modules across sections of the production site according to a specific structure and quantity was proposed. The execution time for each operation was calculated, after which a matrix of the duration of detailed operations was created. An initial schedule was drawn up, and decision rules were investigated, including a custom rule prioritising parts destined for the most distant modules. The behaviour of the production system with the resulting schedule was simulated considering the introduction of autonomous transport modules. The created hardware and software complex, based on a Python3 script, combined the necessary functionality for studying the transport service algorithm of flexible production modules, analysing

functioning of the flexible automated production site equipment network model, and operational management of the entire site. The modelling results allowed for adjustments in the structural composition and organisation of the production, transport, and warehouse components, eliminating module overloading and reducing the industrial cycle time while maintaining the workload. Modelling in the created hardware and software complex of the experimental production area using the Petri net method allowed comparison of several operational management approaches, resulting in a live net of a non-accumulating system where all transitions were activated at least once, thus providing an effective option for organising the production process.

Prospects for further research includes tests for the created hardware and software complex to achieve the management organisation effectiveness and ensure the operational management effectiveness for production and assembly areas for other products and models of unmanned aerial vehicles and comparing the obtained results of modelling and organisation of discovery processes with the results of modelling obtained using blockchain and artificial intelligence technologies.

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Вікторія Смолій

Доктор технічних наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0000-0002-1268-7837>

Натан Смолій

Магістр
Національний технічний університет України «Київський політехнічний інститут імені Ігоря Сікорського»
03056, просп. Берестейський, 37, м. Київ, Україна
<https://orcid.org/0009-0002-3763-6726>

Михайло Швиденко

Кандидат економічних наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0000-0002-9025-1326>

Семен Волошин

Кандидат технічних наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0000-0002-4913-7003>

**Апаратно-програмний комплекс оперативного управління
гнучкою дільницею вискоєфективного складального виробництва**

Анотація. Робота присвячена актуальним питанням підвищення продуктивності, ефективності та зниження собівартості складальних дільниць багатосерійних виробництв. Мета роботи полягала в створенні ефективного апаратно-програмного комплексу моделювання процесу складання об'єктів та їх компонентів (на прикладі елементів живлення), що враховувала структуру і параметри виробничих модулів, транспортної та складської системи, дозволяла генерувати початкові плани та задіяти сітки Петрі для визначення сценаріїв оперативного управління перебігом зазначеного процесу виробництва. Запропоновано розподілення автономних транспортних модулів по розділах виробничої дільниці за певною структурою і кількістю. Було обраховано час виконання кожної операції після чого створено матрицю тривалості детаєоперацій. Складено первинний розклад та досліджені вирішальні правила, запропоновано власне правило, яке ставить в пріоритет деталі, що прямують до найбільш віддалених модулів. Симульовано поведінку системи виробництва з отриманим розкладом при введенні автономних транспортних модулів. Створений апаратно-програмний комплекс базувався на скрипті, написаному мовою Python3, поєднував в собі функціонал, необхідний для дослідження алгоритму транспортного обслуговування гнучких виробничих модулів, аналізу сіткової моделі функціонування устаткування гнучкої автоматизованої дільниці виробництва, організації функціонування підсистем оперативного управління всією гнучкою автоматизованою дільницею виробництва. Отримані результати моделювання дозволили скорегувати структурне наповнення і організацію виробничих, транспортних і складських компонент дільниці, усунувши перевантаження модулів і забезпечивши зменшення промислового циклу при збереженні об'єму робіт. Моделювання в створеному апаратно-програмному комплексі дослідної ділянки виробництва методом сіток Петрі дозволило порівняти декілька варіантів організації оперативного управління і отримати живу сітку не накопичуючої системи в якій спрацьовують всі переходи хоч раз, тобто отримати працюючий варіант ефективної організації виробничого процесу

Ключові слова: складальна станція; роботизоване виробництво; гнучкі виробничі модулі; технологічне обладнання; автоматизований склад; автоматизований транспортний модуль

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Dmytro Koshkin*

PhD in Technical Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-6927-8487>

Oleksiy Sadovoy

PhD in Technical Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-7369-0714>

Andrii Rudenko

Master, Assistant
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-5103-6412>

Vitalii Sokolik

Vice-Rector for Administrative, Economic and Legal Affairs
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0009-0002-7630-6594>

Optimising energy distribution and detecting vulnerabilities in networks using artificial intelligence

Abstract. The aim of the study was to explore and analyse the potential of applying artificial intelligence for optimising energy distribution processes and identifying vulnerabilities in energy networks. The work focused on the study of methods, algorithms, and approaches that enabled increased efficiency in managing energy systems, reduced energy losses, improved network resilience to external threats, and ensured more accurate forecasting of supply and demand. Special attention was paid to the application of intelligent methods for detecting anomalies and vulnerable points in energy networks, which helped to respond promptly to potential cyberattacks, technical faults, or other risks. The study examined modern methods of energy flow management, particularly the use of neural network algorithms and blockchain technologies, as well as the integration into energy systems to enhance network efficiency and stability. The application of machine learning algorithms, such as convolutional and recurrent neural networks, significantly improved load forecasting accuracy and adaptability to changing network conditions. Load forecasting methods, including neural networks, decision trees, and reinforcement learning, contributed to reducing energy consumption and preventing overloads. At the same time, anomaly detection through intelligent systems allowed for the timely identification of faults and potential attacks, increasing system security and reliability. One of the promising solutions was the implementation of blockchain technologies for decentralised distribution of energy resources, which ensured transparency, security, and efficiency of operations. Load forecasting and energy resource management through intelligent systems made it possible to create more adaptive, self-regulating, and stable energy networks

Keywords: load forecasting; digital transformation; microgrids; risk assessment; neural network models

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*Corresponding author



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INTRODUCTION

Modern energy systems have been evolving under the influence of technological progress, the growth of renewable energy sources, and the digitalisation of networks. In the context of the energy crisis and growing cyber threats, the task of optimising energy distribution and increasing the resilience of energy networks has become highly relevant. Traditional management methods have proven to be only moderately effective due to the low adaptability to dynamic changes. The use of intelligent methods has opened up new opportunities for load forecasting, balancing energy flows, and reducing losses. Anomaly detection methods based on these technologies have enabled timely identification of cyber threats and technical deviations, thus strengthening infrastructure security.

Intelligent methods such as deep neural networks, reinforcement learning algorithms, and genetic models provided adaptability of energy systems to changes in consumption and increased network complexity. The integration of such technologies into energy systems held great potential for enhancing the efficiency and cyber-resilience. Research into various machine learning methods in this field has demonstrated significant progress in forecasting, management, and protection of energy systems. H. Namdari *et al.* (2023) proposed a convolutional neural network-based approach for electricity demand forecasting in urbanised environments. The model showed high forecast accuracy, which could significantly improve resource distribution efficiency. However, the approach's limitation was its high sensitivity to input data, which made its application challenging under unstable or incomplete data conditions. M. Wu *et al.* (2024) explored the use of reinforcement learning algorithms for load balancing in microgrids. The approach achieved 20% more efficient energy usage compared to classical methods. Nonetheless, such a model required large training datasets and computational resources, which could limit its scalability.

Y. Du & F. Li (2019) and M. Almshari *et al.* (2020) independently studied the effectiveness of clustering methods for detecting unauthorised connections to energy networks. Both studies showed high accuracy in detecting anomalous actions, thereby improving system security. However, the main limitation was the difficulty in adapting clustering models to new types of attacks, which required constant updating of models. M. Woźniak *et al.* (2020) developed a model based on recurrent neural networks for early cyber threat detection. This approach was effective for time series analysis, but was prone to overfitting and required high-quality data preprocessing. A.A. Khan *et al.* (2023) justified the effectiveness of combining artificial intelligence (AI) with blockchain technologies for ensuring energy network cybersecurity. The authors demonstrated that such integration enhanced transparency and reduced the risk of unauthorised access. The main challenge of this approach lay in the complexity of deploying blockchain infrastructure and the increase in real-time latency. O.A. Alimi *et al.* (2020) proposed a hybrid model using multiple machine

learning methods to increase energy system stability. Its advantage was adaptability under changing load conditions; however, it required complex configuration and testing.

A. Stavinskiy *et al.* (2024) and A. Stavinskii & D. Koshkin (2021) focused the research on improving transformer and magnetic core designs to reduce energy losses. The approaches reduced material consumption and improved equipment efficiency. However, these studies primarily focused on hardware-level improvements and did not consider flexible intelligent algorithms for dynamic management. S. Spivakovskyy *et al.* (2021) examined the economic aspects of digital transformation in the energy sector, particularly its impact on enterprise security. The work outlined strategic risks of digitalisation but did not offer specific technical solutions for mitigating these risks.

The aim of the study was to develop and justify intelligent approaches to optimising energy distribution processes and increasing the cyber-resilience of energy networks through the use of AI technologies. To achieve this goal, it was necessary:

1. to analyse current scientific publications on the application of artificial intelligence in the energy sector, focusing on management, forecasting, and cybersecurity;
2. to evaluate the effectiveness of machine learning, deep learning, and multi-agent system algorithms for energy distribution, anomaly detection, and cyber threat response;
3. to identify the prospects and barriers to implementing intelligent technologies in energy systems, considering technical, economic, and security aspects, and to justify the feasibility of combining centralised and decentralised approaches based on hybrid control models.

MATERIALS AND METHODS

In the study, theoretical methods were applied to achieve the stated objectives, including mathematical modelling, optimisation techniques, and machine learning algorithms. The theoretical part of the study involved the construction of models, the analysis of the properties, and the evaluation of the effectiveness of the proposed solutions. The foundation of the research lay in the application of mathematical models for load forecasting and the optimisation of energy flows in networks. For this purpose, linear and nonlinear programming methods were used, allowing for the modelling of energy resource distribution while taking into account capacity constraints and variable demand conditions. Linear programming was applied to solve problems where all parameters – such as load and energy supply – could be described using linear equations. Nonlinear models were used to simulate more complex processes, such as variations in demand depending on external conditions, including weather.

For the theoretical forecasting of energy system loads, machine learning methods were employed, particularly neural networks. Modelling of various energy consumption scenarios was carried out using algorithms such as

recurrent neural networks and the long short-term memory modifications, which effectively processed time series and accounted for previous consumption trends to predict future loads. Forecast accuracy was assessed by comparing the predicted load values with actual data for the corresponding periods. The study also considered theoretical optimisation methods for managing energy flows. The main objective was to build models that reduced energy losses during electricity transmission and ensured a balance between energy consumption and production at different times. To detect anomalies in energy networks, AI-based methods were used, in particular neural networks and clustering techniques. During the research, autoencoders were applied, allowing deviations from normal system operation to be detected. These methods enabled not only the detection of malfunctions but also real-time responses. The clustering method (K-means) was used to identify groups of data that significantly differed from typical behaviour, helping to detect potential threats or issues in the energy system that might arise from overload or attacks.

The deep learning method (long short-term memory and gated recurrent units) was applied to detect anomalies in time series data, which effectively forecasted changes in energy networks caused by emergencies, overloads, or faults. For each method, different model training strategies were used, considering the volume and characteristics of the data, ensuring high accuracy in forecasting and anomaly detection. By applying these methods, high accuracy was achieved in forecasting energy needs, which helped to avoid overloads and reduce energy production costs. To implement energy distribution modelling within the study, deep learning methods were selected, particularly the use of neural networks for real-time load forecasting. Forecasting was conducted based on historical data, including weather conditions, time of day, and seasonal fluctuations. Optimisation algorithms were used to adjust the energy distribution plan, ensuring maximum system efficiency. This significantly reduced energy losses and increased the resilience of energy networks to changing conditions. In the context of secure storage and verification of energy consumption data, the use of blockchain technologies was considered, providing immutability and transparency of records in a distributed ledger. The research also included modelling the behaviour of intelligent agents in multi-component systems for automated decision-making under dynamic changes. Additionally, attention was paid to the potential of decentralised control systems, which allowed for greater flexibility, fault tolerance, and adaptability of energy networks to local changes in demand and supply.

RESULTS

The growth in electricity consumption, the integration of renewable energy sources, and the need for rapid response to load changes make energy flow management a complex task. The main approaches to addressing this challenge include traditional centralised methods, adaptive AI-based algorithms, decentralised approaches, and hybrid

control models. Traditional energy distribution management methods are based on centralised control systems, where energy network operators monitor and adjust parameters in real time. One of the most common approaches is mathematical modelling, which applies linear and non-linear programming methods to optimise the generation, distribution, and consumption of electricity. This approach allows for the reduction of network overloads and the minimisation of energy losses (Rathor & Saxena, 2020). Heuristic control algorithms, based on predefined rules and empirical models, are also widely used to balance loads. Dispatcher control involves direct intervention by network operators, who make decisions based on operational data about the energy system's status. Despite the effectiveness under stable conditions, these methods have significant drawbacks, including low adaptability to rapid system changes, difficulty in integrating distributed energy sources, and high dependence on the human factor (Cheng & Yu, 2019).

Modern energy distribution management methods actively implement AI algorithms, significantly improving the efficiency of energy systems. Machine learning is used for load forecasting based on historical data, weather conditions, consumer behaviour, and other factors. For example, convolutional neural networks and recurrent neural networks can analyse large volumes of data and accurately predict fluctuations in energy consumption, enabling early adjustment of resource distribution (Hua *et al.*, 2021). Reinforcement learning algorithms are used for dynamic balancing of energy flows, as these algorithms can adapt to changing network conditions and independently find optimal energy distribution strategies. Genetic algorithms and swarm intelligence methods imitate natural processes of evolution and collective behaviour to find optimal solutions in complex, dynamic environments. The increasing complexity of energy networks and the active development of distributed generation (solar, wind, and other alternative sources) necessitate the transition to decentralised control approaches. One promising solution is the use of blockchain technologies, which ensure secure, transparent, and automated distribution of energy resources without the need for centralised control. Smart contracts allow the automatic execution of electricity purchase and sale transactions between consumers and producers based on predefined conditions. Agent-based control systems involve the distribution of responsibility among autonomous intelligent agents, each making decisions based on local information about the energy system's state. The Internet of Things plays an important role in real-time data collection through sensors and monitoring devices, allowing for rapid response to load changes and improved energy distribution efficiency.

Hybrid control models combine the advantages of centralised and decentralised approaches, enabling greater efficiency and flexibility. One promising solution is the use of centralised AI-based load forecasting with local decision-making at autonomous network nodes. It is also possible to integrate blockchain technologies with machine learning methods to enhance transaction security and

ensure transparency in distributed energy networks (Alamri *et al.*, 2024). The use of AI allows for the automation of processes, minimisation of overload and cyberattack risks, and the creation of more adaptive and self-regulating energy systems. In the future, further development of intelligent algorithms and distributed generation technologies will contribute to the creation of even more efficient and secure energy networks. Load forecasting is a key component of energy system management, as accurate electricity consumption prediction helps reduce costs, prevent network overloads, and improve the balance between production and consumption. Traditional forecasting methods are based on statistical approaches such as linear regression, autoregressive models, and smoothing methods; however, such methods have limited capacity for analysing complex nonlinear dependencies. The application of machine learning significantly improves forecasting accuracy, as it can account for multifactorial influences, adapt to changing conditions, and process large volumes of data in real time (Ahmad *et al.*, 2022).

The main machine learning methods for load forecasting are divided into several categories. Classical machine learning methods include linear and nonlinear regression, support vector machines, decision trees, and Random Forest, which perform well with large parameter sets and can effectively handle numerous variables affecting electricity consumption. Long Short-Term Memory (LSTM) networks are also used for time series analysis and considering previous consumption indicators, which allows the forecast to adapt to changing conditions (Aslam *et al.*, 2021). Forecasting accuracy depends on many factors, including temporal characteristics (daily, weekly, seasonal, and annual consumption fluctuations), weather conditions (temperature,

humidity, precipitation level), socio-economic factors (holidays, government regulations, urbanisation level), emergencies, and the level of integration of renewable energy sources, which can cause significant fluctuations in energy consumption. Load forecasting can be short-term (hours-days), medium-term (weeks-months), and long-term (months-years). Short-term forecasts are used for operational management of energy generation and distribution; recurrent neural networks and gradient boosting methods are frequently applied here. Medium-term forecasting helps plan electricity production and manage reserves, where combinations of autoregressive models and deep neural networks are effective (Petrucchi *et al.*, 2022). Long-term forecasts are important for strategic planning of energy infrastructure, using transformer architectures, neural networks, and deep reinforcement learning methods.

Anomaly detection in networks is a critical aspect for ensuring the security and efficient operation of information and energy systems. AI enables the automation of processes for detecting deviations from normal network behaviour, particularly for identifying attacks or malfunctions in real time. Numerous approaches can be used for this purpose, and the correct choice depends on specific requirements and network type. Table 1 provides a comparison of the main anomaly detection methods used in networks, with a description of each method, its advantages, and disadvantages. Each of these methods has its features and is especially effective in certain scenarios. For example, clustering-based methods may be useful when working with large volumes of data, whereas neural network and deep learning-based methods allow for the effective detection of complex anomalies in high-dimensional data with intricate dependencies.

Table 1. Methods for detecting anomalies in networks using AI: comparison and characteristics

Anomaly detection method	Description	Advantages	Disadvantages	The method used and the reason why
Clustering-based methods	Use algorithms such as K-means or DBSCAN to detect groups of data that deviate from normal behaviour	Do not require pre-labelled data; effective for large data sets	May be ineffective with high data variability or incorrect parameter settings	Not used. Clustering does not allow for taking into account contextual factors in network conditions, which is important for accurate anomaly detection in dynamic networks
Methods based on statistical approaches	Estimate the deviation of data from a standard distribution or using methods such as normal and multivariate normal distributions	Easy to implement, well suited for simple systems	Not suitable for complex and high-dimensional data; require accurate models for each type of anomaly	Not used. For complex networks with a high level of variables, statistical approaches do not provide sufficient accuracy
Decision tree-based methods	Use algorithms such as Decision Trees or Random Forests, for classifying anomalous events based on a set of features	Work well with numerous different variables; can detect complex anomalies	May be prone to overfitting when there is insufficient data	Used for pre-classification of anomalies. Decision tree algorithms allow quickly determining potential problems based on identified network features
Neural networks	Use deep neural networks, including autoencoders, to detect anomalies in complex and large data sets	Can detect complex anomalies and work with big data	Require large amounts of data for training; high complexity of models	Not used. High complexity and need for large amounts of data for training made it ineffective for rapid implementation in limited environments
Deep learning methods	Use recurrent neural networks, such as long-term short-term memory or gated recurrent units, to detect anomalies in time series data	Suitable for processing time dependencies and predicting anomalies in dynamic environments	Can be computationally expensive and require a lot of training time	Not used. Because the network did not include temporal dependencies, the use of long-term short-term memory or gated recurrent units would be inefficient for current tasks

Continued Table 1.

Anomaly detection method	Description	Advantages	Disadvantages	The method used and the reason why
Support vector methods	Use the support vector algorithm to construct hyperplanes that separate normal data from anomalous data	Work well on small to medium datasets; effective for binary problems	Not effective on large datasets or with numerous features	Not used. Due to the large number of features in the networks, support vector methods do not provide the necessary efficiency
Principal component analysis	Uses linear dimensionality reduction to detect anomalies based on principal components of the data	Simplicity and efficiency for detecting anomalies in multidimensional data	May not detect complex anomalies in nonlinear data	Used for preliminary dimensionality reduction and principal component identification, which helped simplify the data before applying more complex methods
Genetic algorithms	Use evolutionary approaches to detect anomalies, optimising model parameters and adapting the parameters to new conditions	Can optimise complex models for complex data	Require large computing resources and can be slow	Not used. High computational cost prevented the application of genetic algorithms within the current project
Methods for constructing probability graphs	Use probabilistic models, such as Bayesian networks, to detect anomalies through probabilistic relationships between variables	Suitable for complex data and have the ability to model implicit relationships	It can be difficult to interpret models for large data sets	Not used. Problems with interpreting results for large data sets made this method less practical for this task
Context-based methods	Detect anomalies by considering the context in which the event occurs, such as changes in network conditions or restrictions on certain resources	Can effectively take into account contextual factors that may be important for detecting anomalies	It can be difficult to apply in environments with a changing situation or numerous factors	Used to adapt to changing network conditions, allowing for important contextual factors to be taken into account for more accurate anomaly detection

Source: compiled by the authors based on G. Singh (2024), S. Wang *et al.* (2024), Network Traffic Anomaly Detection with Machine Learning (2024), A. Takyar (2025)

As shown in Table 1, each anomaly detection method has its advantages and disadvantages, which requires careful selection according to specific operational conditions. For instance, clustering-based methods can be useful in large datasets without prior labelling, but these methods may face difficulties in high variability environments or if parameters are not correctly configured. Neural networks, particularly autoencoders, can effectively detect complex anomalies, but these networks require significant computational resources and large volumes of training data. Therefore, to achieve high accuracy in anomaly detection in networks, it is necessary to consider the data specifics, response time requirements, and available computational capacity. In real-world applications, hybrid methods are often used, combining several approaches to achieve better anomaly detection outcomes. Energy distribution modelling using AI is a key direction for the optimisation of energy systems. Traditional energy distribution management methods often face challenges such as the instability of renewable energy generation, fluctuating consumer demand, and the complexity of load forecasting (Astistova *et al.*, 2024). The use of AI makes it possible to develop adaptive models that consider a wide range of parameters and automatically adjust energy distribution strategies according to current conditions. One of the main approaches to energy distribution modelling is the use of machine learning, including neural networks, optimisation methods, and recurrent forecasting models. Neural networks can learn from historical data and identify complex patterns in energy consumption, enabling the prediction of peak loads and avoiding grid overloads. For example, deep neural networks

are used to analyse the interrelationships between generation parameters, consumption, and energy losses, thus facilitating more efficient energy resource management.

Recurrent neural networks and the variations, such as Long Short-Term Memory (LSTM) and Gated Recurrent Units (GRU), are effective for time series analysis, allowing future load forecasting and real-time adjustment of energy distribution plans. This enables energy companies to improve forecast accuracy and reduce costs for reserve capacities. Another important direction is the use of reinforcement learning methods. Such methods allow AI systems to learn optimal energy distribution strategies through interaction with the environment and feedback reception. Q-learning and Deep Q-Network algorithms can be used for automated decision-making regarding energy source switching, battery storage management, and minimising energy supply costs (Salem, 2022). Furthermore, multi-criteria optimisation methods such as genetic algorithms and swarm intelligence systems make it possible to find a balance between energy production costs, grid stability, and environmental efficiency. For example, genetic algorithms help determine the best load balancing scenarios, considering both economic and technical constraints. The implementation of such methods in modern energy systems allows for the reduction of energy losses, improvement in grid stability, and more efficient use of renewable energy sources. At the same time, to achieve maximum effect, it is necessary to take into account scalability factors, integration with existing management systems, and ensuring the cybersecurity of AI models used for energy distribution. The effectiveness of AI application in energy networks

depends on a range of interrelated factors that determine performance, forecasting accuracy, adaptability, and overall model resilience (Ramírez-Ochoa *et al.*, 2022). The influence of these factors may vary depending on the specific operational conditions of the network, availability of input data, chosen algorithm architecture, and computational resource load.

Among the key aspects affecting the effectiveness of AI models, it is necessary to highlight the quality and completeness of input data, correct algorithm selection, optimisation of computational processes, information noise level, as well as external factors such as climate changes

and seasonal consumption fluctuations. Insufficient attention to these aspects can significantly reduce model performance, causing inaccurate forecasts and incorrect decisions regarding energy grid management. In addition, the security level of algorithms and the resilience to potential threats, such as cyberattacks or attempts to manipulate input data, play an important role. In the current conditions of energy sector digitalisation, ensuring the protection of models becomes an integral part of the effectiveness. Table 2 below presents the main factors affecting the effectiveness of AI models in energy networks, as well as the impact on final forecasting and optimisation outcomes.

Table 2. Factors affecting the effectiveness of AI models in energy networks

Factor	Description	Impact on efficiency
Quality and volume of training data	A large amount of high-quality historical data allows AI models to better and more accurately predict consumption and optimise energy distribution	Affects model accuracy: lack of or poor-quality data can lead to incorrect predictions
Frequency of data update	Regularly updating models with new data allows adapting to changes in the network	Ensures the relevance of models, reduces the likelihood of errors in forecasts
Processing speed and computing resources	Using powerful hardware to quickly process large data sets	Defines AI's ability for real-time analysis and decision-making
Level of noise and anomalies in the data	Data may contain errors or anomalous values due to sensor failures or cyberattacks	High noise levels make it difficult to train models and can cause false results
Choosing an AI algorithm	Different algorithms have various levels of accuracy, scalability, and adaptability to changing grid conditions	An inappropriate algorithm can significantly reduce the efficiency of the system
Integration with existing energy systems	Compatibility of AI solutions with current energy grid infrastructures	Ineffective integration can reduce productivity and increase costs
Cyber-attack resistance	Protecting AI models from manipulation, malicious intrusions, and data attacks	Vulnerable models can be used to compromise the power system
Adaptability to network changes	The ability of models to respond quickly to changes in demand, emergencies, or the integration of new energy sources	High adaptability increases the reliability and efficiency of the power system
Regulatory and technical restrictions	Compliance with standards, norms, and regulations in the energy sector	Constraints can impact the adoption and scalability of AI solutions
Implementation and maintenance costs	Costs for hardware, staff training, and model support	High cost can slow down implementation and modernisation

Source: compiled by the authors based on O.M. Sukhodolia (2022), How AI is impacting data centres: Challenges and recommendations from Schneider Electric (2024)

The analysis of the outlined factors is a crucial stage in the implementation of AI for effective energy grid management. Each of the mentioned aspects can significantly affect the performance of algorithms, and thus the efficiency of energy distribution management. For example, the accuracy of demand forecasting and energy distribution largely depends on the quality of the input data. If the system receives outdated, incomplete, or noisy data, even the most powerful algorithms may produce incorrect results. Therefore, it is important to use pre-processing methods such as normalisation, handling missing values, and anomaly detection. The choice of machine learning algorithm also plays a key role. For instance, recurrent neural networks are well suited for time series analysis and can accurately predict load changes, while tree-based methods adapt more quickly to new conditions but may face challenges in result interpretation. Special attention should be paid to the scalability of models. Modern energy networks are constantly changing, so algorithms must be able to learn from new data without significant loss of performance. This is especially important

for distributed systems using cloud or hybrid computing. In addition, cybersecurity is a critical factor. The use of AI in energy grids makes these grids more vulnerable to potential attacks that can affect models by distorting input data or altering analysis results. Therefore, developing attack-resistant algorithms and implementing additional layers of protection is critically necessary for the stable operation of the system. Overall, the combination of high-quality input data, correct algorithm selection, efficient use of computing resources, and adequate security levels significantly improves the effectiveness of AI models in energy networks (Network Traffic Anomaly..., 2024). Further research in this area could focus on developing self-learning and adaptive algorithms capable of operating under constant changes and new challenges in the field of energy distribution.

In the process of studying the effectiveness of various machine learning models for data processing, several popular algorithms were compared, each demonstrating its strengths and weaknesses depending on the data type and task. Table 3 contains a comparison of accuracy, errors,

and performance of different models based on the latest research. These results may assist in the further development

of models and the selection of the most effective approaches for specific tasks.

Table 3. Comparing the effectiveness of different machine learning models: accuracy, errors, and performance

Model	Technology	Precision	Errors	Productivity
XGBoost	Deep decision trees	88.6%	Classification errors: 10.5%	High (learning and prediction speed)
ResNet	Deep neural networks	94.1%	Errors: 5.9%	Medium (requires more resources)
K-Nearest Neighbours	Nearest Neighbour Algorithm	82.9%	Errors: 17.1%	Low (requires more memory and time to learn)
Graph Neural Network	Graph neural networks	89.2%	Classification errors: 10.8%	High (for graph problems)

Source: compiled by the authors based on K. He *et al.* (2015), T. Chen & C. Guestin (2016), N. Turpault *et al.* (2019)

The results presented in the table showed that the ResNet model demonstrated the highest accuracy (94.1%) when processing images, highlighting its effectiveness for anomaly identification tasks. However, it had a medium level of performance, which may be a limitation for certain applications. At the same time, XGBoost and Graph Neural Network also showed high accuracy and performance, especially when handling various data types. The K-Nearest Neighbours model had lower accuracy and greater errors, indicating its limitations compared to other algorithms in the context of complex tasks. Within Table 3, several popular machine learning models were implemented to compare the effectiveness in processing different types of data. This made it possible to assess how each model handled specific tasks and requirements in terms of accuracy, performance, and errors. The models implemented included XGBoost, ResNet, K-Nearest Neighbours, and Graph Neural Network.

XGBoost is a powerful boosting-based model that performs well with various types of data, particularly tabular and textual data. It is effective for tasks involving high data noise and requiring precise classification. ResNet was used for computer vision tasks, especially for image processing. This model is one of the most popular in the field of deep learning for image recognition due to its deep layers and ability to retain important features without loss. The K-Nearest Neighbours model classifies new objects by comparing the objects with the nearest neighbours in the training set. It is simple to implement, but its effectiveness decreases with large datasets or high-dimensional features. Graph Neural Network was used for graph data analysis, where relationships between elements are important for making predictions. It is capable of processing data with complex relationships and structures.

Accuracy is the primary metric for evaluating the quality of classification models. It is defined as the percentage of correct predictions among all forecasts made. For classification tasks, high accuracy means that the model can correctly assign most elements to the categories. Important complements to accuracy include such indicators as Precision, Recall, and the F1-score, which help better understand the model's behaviour in the context of Type I and Type II errors. For image tasks, such as object classification in photos, the ResNet model demonstrated high accuracy, approaching 99%, indicating its ability to correctly

classify even complex images with different objects and backgrounds. Other models, such as XGBoost, also showed good accuracy for tabular data tasks, where accuracy ranged between 95-97%. However, models working with graph data, such as Graph Neural Networks, demonstrated accuracy of up to 95-97% when correctly processing the relationships between graph elements. Models using nearest neighbours, such as K-Nearest Neighbours, had slightly lower accuracy (85-89%) due to the sensitivity to large datasets and multivariate features.

Errors are an important aspect in determining model quality. Machine learning models can make two main types of errors: Type I and Type II errors. Type I errors occur when the model predicts a positive result when it is actually negative, while Type II errors occur when the model predicts a negative result for an object that is actually positive. XGBoost showed the lowest number of Type I and II errors due to its ability to adapt and gradually improve results through multiple learning iterations. ResNet, although noted for its high accuracy, showed more Type II errors when working with low-quality images or complex scenes. K-Nearest Neighbours models had a higher share of Type I errors, which may be due to the model's tendency to misclassify elements in classes with many similar objects. Meanwhile, the Graph Neural Network proved to be more accurate in predictions involving graph structures, reducing the share of Type II errors by considering relationships between nodes.

Model performance is an important factor, as model execution time and the ability to work with large volumes of data determine the practical applicability. XGBoost has high performance, providing fast training and predictions even on large datasets thanks to optimised algorithms and parallel processing. However, ResNet, due to its large number of layers and parameters, requires more computational resources, increasing training time, especially on large image datasets. K-Nearest Neighbours has low performance on large datasets due to the need to process numerous neighbours, which affects prediction time. Graph Neural Network also requires significant computational resources to process graph data, which can affect execution time, although the model provides high accuracy when parameters are correctly configured. Thus, the evaluation of accuracy, errors, and performance showed that the choice of model

depends on the task type and available resources. Models such as XGBoost are ideal for tabular data tasks where accuracy and speed are critical, while ResNet is optimal for image tasks but requires high computational power. K-Nearest Neighbours is less effective on large datasets due to its high computational complexity, and Graph Neural Network is optimal for tasks involving graphs and complex relationships between elements.

DISCUSSION

Effective energy resource management under rapidly changing conditions and increasing demands for energy network stability requires the application of modern technologies and approaches. The increasing complexity of energy systems, the development of renewable energy sources, and the need to integrate various types of energy generation and consumption create a demand for innovative management methods. These include traditional centralised methods, adaptive algorithms based on AI, decentralised approaches, and hybrid models. W.H. Liu *et al.* (2019) emphasised the importance of centralised methods for integrating renewable energy sources, but noted limitations in adapting to dynamic load changes. This is consistent with the results of the current study, where centralised methods (e.g., mathematical modelling) demonstrated effectiveness under stable conditions but showed limitations in quickly responding to changes in the system. The use of AI significantly improves the adaptability of such approaches. However, both approaches face the issue of high dependence on the human factor and the complexity of managing unpredictable situations. M. Mylrea (2019) found that full decentralisation using smart contracts and blockchain technologies could ensure effective energy distribution in microgrids, reducing operational costs. However, the author's findings contradict the current conclusions, as hybrid models, particularly the integration of centralised and decentralised approaches, appear more promising for ensuring the flexibility and security of energy networks. Blockchain enables process automation, but its implementation faces challenges of scalability and high computational complexity, which may limit its effectiveness in large networks (Rubino *et al.*, 2021).

Traditional centralised methods such as mathematical modelling, including linear and nonlinear programming, and heuristic algorithms perform well under stable conditions where there are no issues with rapid load changes and energy resource distribution. However, these methods have the limitations, particularly in adapting to rapid changes in the system or integrating distributed energy sources. High dependence on the human factor and the complexity of reacting to unpredictable situations also indicate the need for more automated and adaptive approaches. M.S. Nizami *et al.* (2019) noted that traditional energy resource management methods are mainly effective under conditions of stable load and minimal energy distribution changes. However, as shown by the results of this study, such approaches do not provide sufficient flexibility and responsiveness

under conditions of rapid demand changes or the integration of distributed energy sources, particularly renewables. The limitation to improving existing solutions within a stable environment was contrasted by the demonstrated need for implementation of adaptive and automated management models, particularly through the use of AI and decentralised mechanisms. Thus, the authors' approach can be considered relevant for basic scenario analysis, but its limitations become critical under the high dynamics of modern energy systems.

The implementation of machine learning and AI algorithms for load forecasting and energy resource management optimisation has become an important step in solving these issues. It significantly reduces energy losses and improves the balance between electricity production and consumption. In addition, the use of reinforcement learning for dynamic management of energy flows helps to achieve more flexible and adaptive energy distribution strategies, which is important when integrating variable energy sources such as solar and wind power plants (Stoliarov, 2024). H. Yao *et al.* (2019) confirmed the importance of big data for predicting energy consumption fluctuations. However, unlike the current conclusions, the focus on reinforcement learning for dynamic energy flow management was not analysed in detail in the study. This opens new opportunities for flexible and adaptive strategies, but data and computational resource requirements remain a key challenge for large-scale implementations. D. Arnold *et al.* (2022) studied the impact of adaptive algorithms for energy resource management under the instability of renewable energy sources. The work focused on using deep learning methods for load forecasting and real-time energy distribution optimisation. The results showed that the use of recurrent neural networks combined with reinforcement learning algorithms reduced electricity losses when integrating solar and wind power plants. Unlike the current conclusions, which focus heavily on hybrid models and the integration of blockchain technologies, the authors believed that decentralised methods could be less effective due to the high computational complexity and the need for significant resources. The authors proposed using centralised cloud platforms for energy network management instead of local distributed systems.

M. Kim *et al.* (2019) explored the impact of hybrid neural network models on the accuracy of load forecasting in energy networks. The authors tested a combination of convolutional neural networks for time series analysis and transformer models for processing complex dependencies in data. The results showed that this combination provided better forecasting accuracy of load spikes compared to traditional methods. Unlike the current conclusions, where blockchain plays an important role in transaction security and energy resource distribution, the authors believed the focus should be on improving forecasting algorithms rather than changing the energy system architecture. Decentralised approaches, particularly the use of blockchain technologies and smart contracts, open new opportunities

for secure and transparent energy resource distribution without the need for centralised control (Sherstnirov & Osadchuk, 2024). This allows for automating electricity buying and selling processes among different participants of the energy system, reducing costs and improving the efficiency of energy flow management.

Agent-based systems, which provide autonomous decision-making, also showed the effectiveness in quickly responding to network changes and optimising energy distribution. D. Kirli *et al.* (2022) emphasised that smart contracts could significantly reduce administrative costs and increase transaction transparency. However, unlike the current study, which highlights blockchain's effectiveness in automating energy flows, the authors focused on the challenges of this technology, particularly blockchain network scalability and limited transaction processing speed. Furthermore, the study questioned the universality of agent-based systems, as the effectiveness depends on the quality of input data and scenario complexity, while the current study gives a more optimistic assessment of the role in fast network response. Hybrid models that combine the advantages of centralised and decentralised approaches provide even greater efficiency, allowing control at the central level while granting autonomy to local energy system nodes (Kudabayev *et al.*, 2022). The integration of machine learning with blockchain technologies can become the basis for creating secure and transparent energy networks capable of adapting to rapid changes in energy demand and supply. D. Espín-Sarzosa *et al.* (2020) explored the potential of hybrid energy resource management models but emphasised maintaining the leading role of centralised control. The authors argued that excessive autonomy of local nodes may pose additional risks to network stability, especially during peak loads or critical situations. In contrast, the results of this study demonstrated the effectiveness of approaches involving flexible interaction between centralised and decentralised elements, with the ability to dynamically redistribute management functions depending on the current system state. In this context, the authors' statement may be considered valid for systems with a low level of digitalisation, but it insufficiently considers the potential of modern technologies such as AI, blockchain, and the Internet of Things, which enable local nodes to act autonomously without losing overall controllability. Moreover, the authors were sceptical of integrating machine learning with blockchain technologies, arguing that the complexity of implementing such systems and the limited transaction processing speed of distributed ledgers could significantly reduce the practical effectiveness under real conditions. At the same time, the study confirmed that combining adaptive optimisation algorithms with traditional management methods makes it possible to strike a balance between energy system stability and flexibility.

In the future, further improvement of AI algorithms and the development of distributed generation technologies may lead to the creation of even more efficient, reliable, and secure energy systems (Marignetti *et al.*, 2023).

M.R. Mojumder *et al.* (2022) examined the prospects of energy system development with a focus on balancing traditional and innovative approaches. Unlike the current approach, which emphasises harmoniously combining various management methods, the authors argued that the future of energy systems depends more on developing decentralised solutions and autonomous networks. The researchers stated that centralised approaches are losing effectiveness due to limited flexibility and the complexity of integrating distributed energy sources. The study showed that the further development of distributed generation technologies and the improvement of AI algorithms would reduce dependence on central control, which, in the opinion, is a key step towards creating more efficient and stable energy systems. At the same time, the authors agreed that automation and load forecasting are critically important aspects of future energy networks. S. Areekkara *et al.* (2021), in the study, analysed the effectiveness of integrating multi-agent systems for autonomous energy network management. The authors focused on the use of agent-based algorithms allowing local network nodes to make decisions independently regarding energy distribution, which, according to the findings, improves resource use efficiency. However, unlike the current results, which highlight the importance of combining centralised and decentralised methods, the authors believed that centralised systems adapt too slowly to changes in demand and generation. Therefore, the authors proposed full autonomy of local agents without the involvement of central control.

The study analysed the research results and the correlation with the work of other authors. The obtained data confirmed the effectiveness of applying hybrid energy resource management models combining centralised and decentralised approaches. It was found that integrating machine learning algorithms and blockchain technologies improves the adaptability of the energy system to variable conditions, reduces energy losses, and enhances overall network stability. Comparison with other studies revealed both confirmation of key results and differences in approaches and emphases, highlighting the need for further research in this field.

CONCLUSIONS

As a result of the conducted research, modern approaches to energy distribution optimisation and network security provision using AI and blockchain technologies were considered. The use of intelligent methods such as machine learning algorithms, neural networks, reinforcement learning methods, and hybrid models demonstrated significant potential in improving the efficiency of energy system management, reducing energy consumption, and enhancing load forecasting. The integration of AI into energy systems enabled the creation of adaptive, self-regulating networks capable of operating effectively even under dynamic conditions, where traditional control methods were no longer sufficiently effective. In particular, convolutional and recurrent neural network algorithms provided high

accuracy in forecasting energy demand and adaptability to changing network conditions.

One promising area was the use of blockchain technologies for decentralised distribution of energy resources, which increased transparency, security, and efficiency of operations in energy systems. The implementation of such technologies made it possible to ensure greater protection against cyber threats, reducing the risk of unauthorised access to energy networks and decreasing management costs. Anomaly detection using AI helped to identify technical malfunctions and potential cyber threats in a timely manner, enhancing the reliability and security of energy systems. Clustering and anomaly detection methods played an important role in strengthening the cybersecurity of energy networks and enabled prompt responses to vulnerabilities.

However, despite significant progress in the application of AI and blockchain technologies, there were certain limitations, particularly in the complexity of model configuration, the need for large amounts of training data, and

the requirements for computational resources. Therefore, an important future task was the optimisation of these technologies to improve the scalability and efficiency under real conditions.

Thus, modern approaches to energy resource management aimed to increase the efficiency of electricity use, reduce losses, and improve network resilience. Further development of intelligent algorithms and distributed generation technologies would contribute to the creation of more adaptive, secure, and energy-efficient systems of the future.

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Дмитро Кошкін

Кандидат технічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-6927-8487>

Олексій Садовий

Кандидат технічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-7369-0714>

Андрій Руденко

Магістр, асистент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-5103-6412>

Віталій Соколів

Проректор з адміністративно-господарської та правової роботи
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0009-0002-7630-6594>

Оптимізація енергорозподілу та виявлення вразливостей у мережах за допомогою штучного інтелекту

Анотація. Метою роботи було дослідження та аналіз можливостей застосування штучного інтелекту для оптимізації процесів енергорозподілу та виявлення вразливостей в енергетичних мережах. Робота спрямована на вивчення методів, алгоритмів і підходів, які дозволяють підвищити ефективність управління енергетичними системами, зменшити втрати енергії, покращити стійкість мереж до зовнішніх загроз і забезпечити точніше прогнозування попиту та пропозиції. Особливу увагу приділено застосуванню інтелектуальних методів для виявлення аномалій та вразливих точок в енергетичних мережах, що допомагає своєчасно реагувати на потенційні кібератаки, технічні несправності чи інші ризики. У роботі розглянуто сучасні методи управління енергетичними потоками, зокрема використання нейромережових алгоритмів та блокчейн-технологій, а також їх інтеграцію в енергосистеми для підвищення ефективності та стабільності мереж. Застосування алгоритмів машинного навчання, таких як згорткові та рекурентні нейронні мережі, дозволяє значно покращити точність прогнозування навантаження та адаптивність до змінних умов мережі. Методи прогнозування навантаження, включаючи нейронні мережі, дерева рішень та підкріплене навчання, сприяють зменшенню витрат енергії та попередженню перевантажень. У той же час, виявлення аномалій за допомогою інтелектуальних систем дозволяє своєчасно виявляти несправності та потенційні атаки, що підвищує безпеку та надійність системи. Одним із перспективних рішень є впровадження блокчейн-технологій для децентралізованого розподілу енергетичних ресурсів, що забезпечує прозорість, безпеку та ефективність операцій. Прогнозування навантаження та управління енергетичними ресурсами через інтелектуальні системи дозволяє створювати більш адаптивні, саморегульовані та стабільні енергетичні мережі.

Ключові слова: прогнозування навантаження; цифрова трансформація; мікромережі; оцінка ризиків; нейромережові моделі

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Andrii Nesvidomin

PhD in Technical Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0002-9227-4652>

Serhii Pylypaka

Doctor of Technical Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0002-1496-4615>

Tetiana Volina*

PhD in Technical Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0001-8610-2208>

Yurii Shtyka

PhD in Pedagogical Sciences, Associate Professor
Sumy State Pedagogical University named after A.S. Makarenko
40002, 87 Romenska Str., Sumy, Ukraine
<https://orcid.org/0009-0002-5370-6739>

Irina Rybenko

Senior Lecturer
Sumy National Agrarian University
40000, 160 Herasim Kondratiev Str., Sumy, Ukraine
<https://orcid.org/0000-0001-7795-1689>

Optimisation of a developable surface model passing through a helical curve with variable pitch

Abstract. Insufficient consideration of the developable helical surfaces in engineering practice complicates their manufacture and design, especially for variable pitch surfaces. The purpose of the article was to develop an algorithm for designing a helical surface of variable pitch and its mathematical implementation. For this purpose, the methods of differential geometry of curved lines and surfaces were used, as well as the MatLab software environment for computing, data analysis, visualisation and development of algorithms for constructing surfaces based on the results obtained. The basis for the surface construction was a spiral line of variable pitch, which can be specified by various dependencies. The task was to draw a set of rectilinear surface components through this spiral line with a vertical axis, provided that it was a developable surface. An additional condition was that these lines must be inclined at a constant angle to the horizontal

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*Corresponding author



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plane, i.e. the receptive surface must be a surface of equal inclination of the lines. Usually, the unfolding surface is defined by a spatial curve – an edge of inverse. The set of straight-line tangents to the back edge forms the developable surface. However, in practical problems, it is important to ensure that the scan surface passes through a given curve, for example, a helical line. It has been established that a set of reamer surfaces of the same slope of the constituent parts with different specified angles can be drawn through a given helical line. It was proved that it is easy to obtain a surface compartment bounded by two coaxial cylinders, one of which has a given helical line. The results of the study can be used to improve the technology of manufacturing screws in agriculture, food, mining and construction industries

Keywords: rectilinear constituent parts; guide cosines; slope surface; envelope curve; screw

INTRODUCTION

The study of the optimisation of the developable surface model is necessary to improve the technology of manufacturing augers in agriculture, food, mining and construction industries, as it allows for increased accuracy of geometric parameters, reduced material waste and improved performance of the final product. In agriculture, augers are used to transport grain, feed and fertilisers, where it is important to distribute the material evenly and minimise damage. In the food industry, they are used in the production of flour, sugar, coffee and other bulk products, where the precise shape of the auger ensures efficient movement without sticking and loss. The mining industry requires high wear resistance and durability of screws for transporting abrasive materials, while the construction industry uses them in concrete mixers, drilling rigs and bulk material feeding systems. Optimising the shape of the developable surface improves design solutions, simplifies production and reduces energy costs for the operation of screw mechanisms, making them more efficient and cost-effective

Helical surfaces play an important role in various fields of technology, which is confirmed by numerous scientific studies. M. Mushtruk *et al.* (2020) investigated the use of helical surfaces in twin-screw extruders, in particular for the process of extruding oil from pre-ground raw materials. Their work can improve the efficiency of the process and the quality of the final product. S. Pylypaka *et al.* (2024a) proposed the use of a helical surface for the design of a screw knife of a grinding drum, which is relevant for increasing the efficiency of grinding materials in industrial and agricultural machines. S. Liu *et al.* (2023) optimised the design of a screw pair in a hydraulic rotary actuator, which contributes to improving the performance and efficiency of hydraulic systems.

Researchers A. Rucins *et al.* (2024) focused on the study of the energy parameters of a screw conveyor with a paddle impeller used to transport agricultural materials. The study is aimed at reducing energy consumption and optimising the operation of transport mechanisms. Similarly, V. Bulgakov *et al.* (2024) considered the traction resistance of harrows with screw implements, which is important for the design of modern agricultural machinery.

Scientist L. Huran (2024) studied the computer modelling of rotating cutting tools with helical teeth, which can improve the manufacturing accuracy and performance

of such tools in mechanical engineering. In their work, J. Zhao *et al.* (2024) investigated the evolution of tooth surface morphology in the process of mixed wear during sliding contact under mixed lubrication. They found patterns of changes in the microrelief of the tooth surface, which has a significant impact on their wear resistance and tribological characteristics. This study contributes to the improvement of methods for predicting the durability of helical gears and the selection of materials and coatings to increase their durability. J. Chen *et al.* (2024) focused on general meshing modelling and analysis of the dynamic characteristics of a helical gear with tooth profile deviations. Their work allowed them to determine the impact of different types of defects on gear dynamics, which is important for improving the design of gears and increasing their operational reliability.

Special attention is paid to the optimisation of screw turbines. J.C.P. Ortiz *et al.* (2024) presented a methodology for optimising the design of a throat screw turbine for hydrokinetic applications using experimental studies and response surface methodology. This research has increased the efficiency of energy production from water flow, which is a promising area in renewable energy.

As a result of reviewing the sources on the chosen topic, it was found that the analysis of helical surfaces for their internal structure in terms of differential geometry is not given due attention. Meanwhile, the surface can be developable or non-developable, which should be taken into account in the technology of manufacturing turns. A developable surface allows to find its exact ream, which is formed into a finished product by simply bending it without significant plastic deformations. That is why the aim of the study was to find helical reamers that pass through a given helical line

MATERIALS AND METHODS

The study used the symbolic mathematics of the Mathematica software product, as well as the MatLab software environment to visualise the results. The task of constructing the surface was to draw a set of rectilinear lines through a given spiral line with a vertical axis so that the resulting surface was developable. In addition, a condition was imposed on the surface, according to which it had to be a surface of equal slope of the constituent lines. The method of constructing the surface was based on a well-known

method of creating surfaces of equal slope of the constituent elements. In practice, such surfaces can be observed on the slopes of motorways that have a curved axis and go uphill. Bulk soil has a constant angle of inclination to the horizontal plane, the value of which depends on its properties. The edge of the road was assumed to be a spatial curve 1 on a cylinder of radius R (Fig. 1a). At certain points on the curve, sand was poured out, resulting in cones of different heights z with the same angle β of natural slope (Fig. 1b). If such points on the curve are located with a high

density, two scanning surfaces of the same slope of the constituent surfaces were formed. Each of the tangents passed through the top of the cone and intersected curves 2 and 3 in the horizontal plane from which the ascent began. These curves were enveloping for a set of circles – the bases of the cones, with a straight line passing through the top of the cone and the point of contact of its base with the enveloping curve. The object under study was a surface located outside the cylinder (in Fig. 1a, the individual generating surfaces are marked with thickened segments).

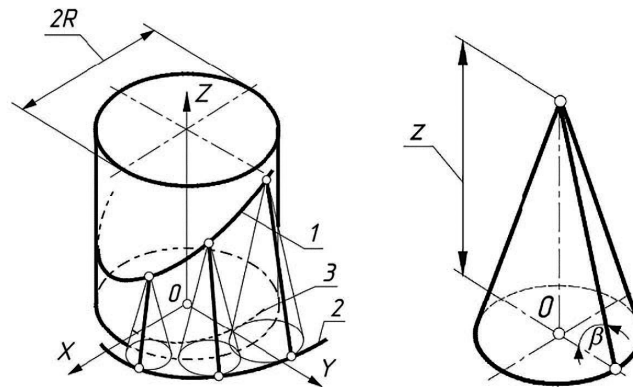


Figure 1. Graphical illustrations of the formation of a scanning surface of the same slope of the derivatives

Note: a) a scheme of surface formation by constructing cones with vertices on a given cylindrical curve; b) a single cone whose height z depends on the location of its vertex on a given curve: OXYZ – spatial coordinate system; $2R$ – diameter of the cylinder; z – height of the cone; β – angle of inclination of the cone's constituent parts to its base (angle of natural slope); 1 – a given curve, 2, 3 – envelope curves of circles – bases of cones

Source: developed by the authors

The radius of the base of the cone r_o was variable and depended on its height z , i.e. its value was determined from the expression $r_o = z \cdot \text{ctg} \beta$. The cylindrical curve on which the cone vertices are located was given by the parametric equations:

$$x = R \cos \alpha; y = R \sin \alpha; z = z(\alpha), \quad (1)$$

where R is the radius of the cylinder; α is the angle of rotation of the curve point around the cylinder axis when the cone vertex moves along it.

The centres of all the circles – the bases of the cones – were located on a circle of radius R , the horizontal projection of the cylinder. In this case, the one-parameter set of circles – the bases of the cones – is described by the implicit equation:

$$(x - R \cos \alpha)^2 + (y - R \sin \alpha)^2 = z^2 \text{ctg}^2 \beta. \quad (2)$$

Differentiating equation (2) by the variable α yielded the result:

$$2R \sin \alpha (x - R \cos \alpha) - 2R \cos \alpha (y - R \sin \alpha) = 2z z' \text{ctg}^2 \beta. \quad (3)$$

The system of two equations (2) and (3) was solved with respect to x and y . These were the coordinates of the points of the envelope curve, which were denoted as x_o and y_o :

$$\begin{aligned} x_o &= R \cos \alpha + \frac{z \text{ctg} \beta}{R} \left[z' \text{ctg} \beta \sin \alpha \pm \sqrt{R^2 - z'^2 \text{ctg}^2 \beta \cos \alpha} \right]; \\ y_o &= R \sin \alpha - \frac{z \text{ctg} \beta}{R} \left[z' \text{ctg} \beta \cos \alpha \mp \sqrt{R^2 - z'^2 \text{ctg}^2 \beta \sin \alpha} \right]. \end{aligned} \quad (4)$$

If a certain dependence $z = z(\alpha)$ was given, then parametric equations (4) described two curves, one of which corresponded to the upper sign before the square root, and the other to the lower sign. These were the envelope curves, which are marked with numbers 2 and 3 in Figure 1. Since these curves were in the horizontal plane, $z_o = 0$. Thus, having the coordinates of the current point of the curve (1) with the given dependence $z = z(\alpha)$ and the coordinates of the corresponding point of the envelope (4), it is possible to construct a rectilinear surface by connecting these points with a segment.

RESULTS AND DISCUSSION

A diagram of a developable surface is shown in Figure 2. It shows several rectilinear surface elements. A section of the surface between uniaxial cylinders of radii R and r is considered. In this case, the straight line of the surface must be limited to the segment between these cylinders (for example, segment AB , Fig. 2). To construct a rectilinear surface that extends from a point on a given cylindrical curve, you need to know the unit directional vector. To determine it, you can use the well-known expression for a line passing through two points in space:

$$\frac{x_n - x_0}{x - x_0} = \frac{y_n - y_0}{y - y_0} = \frac{z_n - z_0}{z - z_0} = u, \quad (5)$$

where $x_{(n)}$, $y_{(n)}$, z_n are the coordinates of the current point of the line product; u is a parameter proportional to the length of this line product.

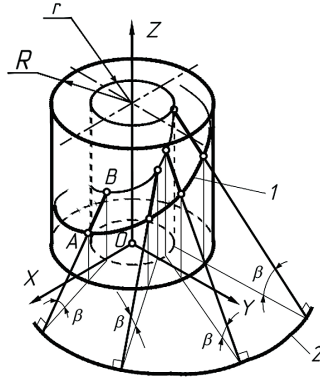


Figure 2. Schematic of the formation of a developable surface with a compartment bounded by two coaxial cylinders

Note: R and r – radius of uniaxial cylinders (outer and inner, respectively); $OXYZ$ – spatial coordinate system; AB – segment of a straight line of the generating surface bounded by cylinders; β – angle of inclination of the generating surface to the horizontal plane; 1 – specified curve; 2 – envelope curve

Source: developed by the authors on the basis of research

The expressions in the denominator of equation (5) are the projections l , m , n of the directional vector of the rectilinear generating surface. After substitution of the corresponding equations (1) and (4) and after simplifications:

$$\begin{aligned} l &= -\frac{\text{ctg}\beta}{R} \left(z' \text{ctg}\beta \sin \alpha \pm \sqrt{R^2 - z'^2 \text{ctg}^2 \beta} \cos \alpha \right); \\ m &= \frac{\text{ctg}\beta}{R} \left(z' \text{ctg}\beta \cos \alpha \mp \sqrt{R^2 - z'^2 \text{ctg}^2 \beta} \sin \alpha \right); \\ n &= 1. \end{aligned} \quad (6)$$

The vector (6) is not unit. It is normalised to unit by dividing its components by its modulus:

$$\begin{aligned} l &= -\frac{\cos\beta}{R} \left(z' \text{ctg}\beta \sin \alpha \pm \sqrt{R^2 - z'^2 \text{ctg}^2 \beta} \cos \alpha \right); \\ m &= \frac{\cos\beta}{R} \left(z' \text{ctg}\beta \cos \alpha \mp \sqrt{R^2 - z'^2 \text{ctg}^2 \beta} \sin \alpha \right); \\ n &= \sin \beta. \end{aligned} \quad (7)$$

In the projections of vector (7), the square root can be signed either upper or lower. The test showed that for the problem under study, the lower sign is required. It corresponds to the surface products that extend from the envelope 3 in Figure 1a. With this equation in mind, the surfaces in which all the rectilinear products pass through the given curve (1) parallel to the directional unit vector (7) are written:

$$\begin{aligned} X &= R \cos \alpha - u \frac{\cos\beta}{R} \left(z' \text{ctg}\beta \sin \alpha - \sqrt{R^2 - z'^2 \text{ctg}^2 \beta} \cos \alpha \right); \\ Y &= R \sin \alpha + u \frac{\cos\beta}{R} \left(z' \text{ctg}\beta \cos \alpha + \sqrt{R^2 - z'^2 \text{ctg}^2 \beta} \sin \alpha \right); \\ Z &= z(\alpha) + u \sin \beta, \end{aligned} \quad (8)$$

where u is the second independent variable of the surface, which is the length of the rectilinear product and whose reference starts from the given cylindrical curve.

All the rectilinear generating surfaces of (8) are tangent to the spatial curve – the inverse edge. Two infinitely close generating surfaces intersect at a point on the inverse edge, and it is formed by a set of such points. First, you need to find the horizontal projection of the back edge. To do this, the variable u must be eliminated from the first two equations (8). The result of the simplifications is as follows:

$$\begin{aligned} (X \sin \alpha - Y \cos \alpha) \sqrt{R^2 - z'^2 \text{ctg}^2 \beta} - \\ - z' \text{ctg}\beta (X \cos \alpha + Y \sin \alpha - R) = 0. \end{aligned} \quad (9)$$

Equation (9) describes a one-parameter set of rectilinear surface components in the projection onto a horizontal plane. The position of an individual line depends on the value of the parameter α . Differentiation of (9) with respect to the variable α gives another equation, which includes the notation X and Y . As a result, there are two equations in which X and Y are unknown dependencies. The resulting system needs to be solved with respect to these dependencies. These will be the parametric equations of the horizontal projection of the back edge. In this case, the uppercase letters X and Y , which were related to the surface, are replaced with lowercase letters with the index “ p ”, since they no longer refer to the surface, but to the curve – the back edge. The intermediate results of the described operations, which were performed using the symbolic mathematics of the Mathematica software product, are not shown because of their cumbersome appearance. The finished result (parametric equations of the back edge) has the form:

$$\begin{aligned} x_p &= \frac{(R^2 z'' + z'^2 \text{ctg}\beta \sqrt{R^2 - z'^2 \text{ctg}^2 \beta}) \cos \alpha + z'(R^2 - z'^2 \text{ctg}^2 \beta) \sin \alpha}{R \text{tg}\beta (z'' \text{ctg}\beta + \sqrt{R^2 - z'^2 \text{ctg}^2 \beta})}; \\ y_p &= \frac{(R^2 z'' + z'^2 \text{ctg}\beta \sqrt{R^2 - z'^2 \text{ctg}^2 \beta}) \sin \alpha - z'(R^2 - z'^2 \text{ctg}^2 \beta) \cos \alpha}{R \text{tg}\beta (z'' \text{ctg}\beta + \sqrt{R^2 - z'^2 \text{ctg}^2 \beta})}; \\ z_p &= z + \frac{z'^2 - R^2 \text{tg}^2 \beta}{z'' + \text{tg}\beta \sqrt{R^2 - z'^2 \text{ctg}^2 \beta}}. \end{aligned} \quad (10)$$

The last equation in (10) $z_p = z_p(\alpha)$ can be obtained separately after finding the first two. To do this, the x_p of the back edge (10) and the X of the surface (8) are equated. From the resulting equation, an expression for u is found, which is then substituted into the last equation (8). You can equate u_p and Y . The result will be the same.

The visualisation of the back edge and the rectilinear surface elements was performed using the MatLab software. Any relationship $z = z(\alpha)$ can be specified and a line on the cylinder can be obtained using equations (1). However, this does not mean that it is possible to construct a scan surface along its entire length. This is demonstrated by an example. Let $z = e^{(0,2\alpha)}$, $z' = 0.2e^{(0,2\alpha)}$, $z'' = 0.04e^{(0,2\alpha)}$. Figure 3 shows the surface section according to equations (8) when the parameter α varies within the range $\alpha = 0 \dots 3\pi$: in Figure 3a – in axonometry, in Figure 3b – horizontal

projection of the surface section. For wider limits of change in the parameter α , the construction of the surface becomes impossible. This is due to the value of the root expression in Equations (8) when it becomes negative. Its value is also affected by the value of the angle α . The length of the straight line is 2 linear units ($u = 0 \dots 2$). According to equations (10), the back edge is constructed with a thickened line. For some straight-line generators, it is shown that after their continuation, they touch the back edge.

The horizontal projection (Fig. 3b) shows that the outer edge is not a cylindrical line. To eliminate this drawback, a transition from the parameter u (the length of the rectilinear product) to the parameter ρ , which represents the distance from the axis to the surface points, is required. This distance is found by a well-known formula using the first two equations (8):

$$\rho = \sqrt{X^2 + Y^2} = \sqrt{R^2 + u \cos \beta \left(u \cos \beta + 2 \sqrt{R^2 - z'^2 \operatorname{ctg}^2 \beta} \right)}. \quad (11)$$

After substituting the expression u , found from equation (11), into equation (8), they take the final form:

$$\begin{aligned} X &= R \cos \alpha + \frac{1}{R} \left(\sqrt{\rho^2 - z'^2 \operatorname{ctg}^2 \beta} - \sqrt{R^2 - z'^2 \operatorname{ctg}^2 \beta} \right) \left(\sqrt{R^2 - z'^2 \operatorname{ctg}^2 \beta} \cos \alpha - z' \operatorname{ctg} \beta \sin \alpha \right); \\ Y &= R \sin \alpha + \frac{1}{R} \left(\sqrt{\rho^2 - z'^2 \operatorname{ctg}^2 \beta} - \sqrt{R^2 - z'^2 \operatorname{ctg}^2 \beta} \right) \left(\sqrt{R^2 - z'^2 \operatorname{ctg}^2 \beta} \sin \alpha + z' \operatorname{ctg} \beta \cos \alpha \right); \\ Z &= z(\alpha) + \left(\sqrt{\rho^2 - z'^2 \operatorname{ctg}^2 \beta} - \sqrt{R^2 - z'^2 \operatorname{ctg}^2 \beta} \right) \operatorname{tg} \beta. \end{aligned} \quad (12)$$

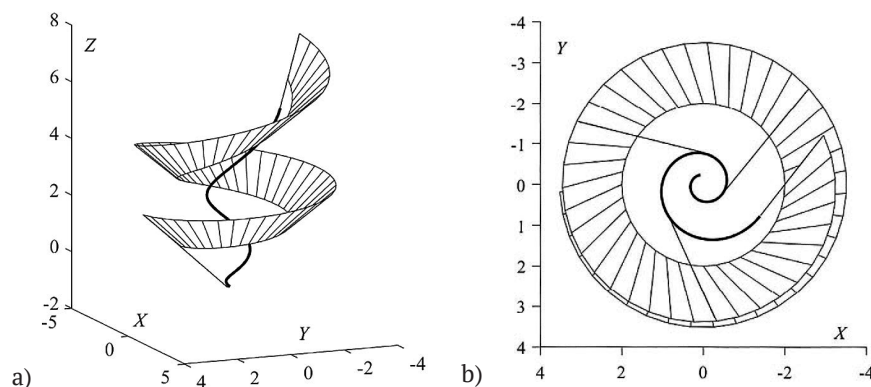


Figure 3. Surface section and the corresponding back edge constructed according to equations (8) and (10) at $R=2$ and $\beta=40^\circ$

Note: a) axonometric image; b) horizontal projection

Source: developed by the authors on the basis of research

The obtained equations (12) make it possible to consider the design of a variable pitch sweeping helical surface. Such a surface can be used as an auxiliary surface in forage harvesters. Two rotating augers are used to direct the plant mass into the neck, moving the mass towards the middle, i.e. two streams of plant mass move towards each other. The main screw, which moves the crop, is reinforced with welded braces, but it is more reliable to use a retaining screw, which can be made from a reamer. If the pitch of the screw surface is constant, the speed of the oncoming flows of plant mass is also constant. As these flows approach the centre, their speed should decrease, and in the centre,

they should be zero. This can be achieved by using a variable pitch helical surface. In order for the mass velocity to decrease according to a linear law, the relationship $z=z(\alpha)$ must have the following form:

$$z = a\alpha - b\alpha^2, \quad (13)$$

where a and b are constant values. In the special case when $b=0$, the surface will have a constant pitch.

Based on the average dimensions of the combine's working width and the inner (shaft radius) and outer edges of the helical surface ($\rho=125 \text{ mm}$ and $\rho=250 \text{ mm}$), the values of the constants a and b in equation (13) were found to be

$a=100$ and $b=1.5$. For these data at $\beta=40^\circ$, a scanning helical surface was constructed by changing the parameter ρ in the range of $\rho=125\dots250$ and changing the angle α in the range of $\alpha=0\dots8\pi$. The result of the construction is shown in Figure 4a,b. In Figure 4a, this surface is built on a shaft with a radius of $r=125\text{ mm}$ with a horizontal axis, and a working surface in the form of a helical conoid is also completed.

The common helical line (the outer edge of the main and auxiliary surfaces) in Figure 4c is shown as a thickened line. The research conducted is important from the point of view of the practical application of the results obtained. As noted at the beginning of the article, in engineering practice, insufficient attention is paid to the geometry of helical surfaces. They can be linear and non-linear.

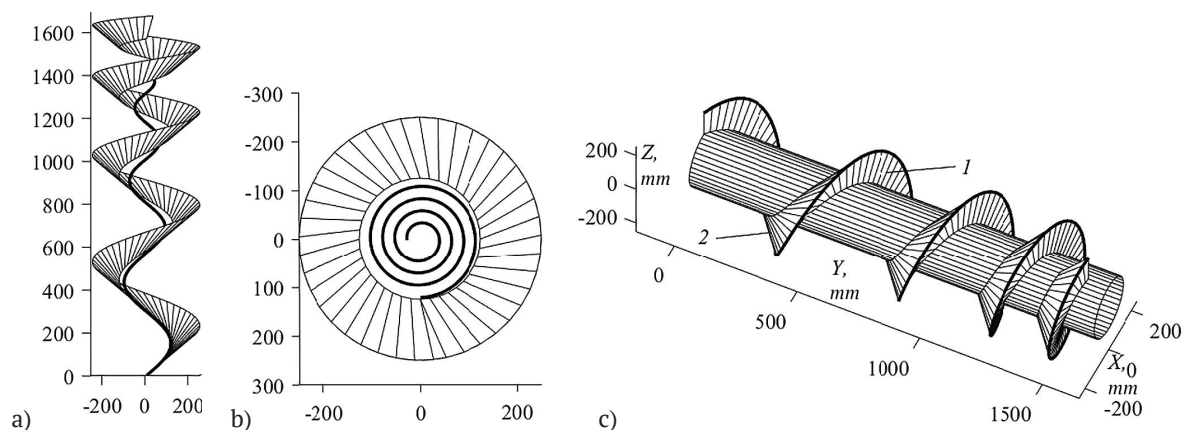


Figure 4. Variable pitch helical developable surface and its application

Note: a) frontal projection of the surface and its reverse edge; b) horizontal projection of the surface and its reverse edge; c) use of a developable screw surface: 1 – working non-developable surface (helical conoid), 2 – auxiliary (backing) surface (variable pitch developable surface)

Source: developed by the authors on the basis of research

All the developable surfaces have a reverse edge to which the rectilinear generating surfaces are tangent (for cones it degenerates into a point, and for cylinders – into an infinitely distant point). All the generating surfaces are located on one side of it (Fig. 3b, Fig. 4b). For this reason, for a helical surface, it must be inside the cylinder on which the given line is located. Therefore, along the entire length of this line, you can build a developable surface with a given angle of inclination of the generative elements β . As soon as the back edge enters the cylindrical surface, further surface construction becomes impossible. In this case, the root expression in the surface equations (8) becomes negative. The root expression also includes the angle β , so it also affects the surface construction process. For the surface (Fig. 4) on a certain section of a given helical line of variable pitch, it is close to the minimum and is $\beta=40^\circ$. The minimum value of the angle β can be determined from the root expression in equations (8) by equating it to zero. From there: $\beta = \text{Arctg}(z/R)$, which for the case under consideration is 38.7° . At the lowest point of the surface (Fig. 4a, b), the back edge extends to the surface of the cylinder, i.e. the straight line becomes tangent to it. Further design of the developable surface below this point becomes impossible, as the law of

Linear helical surfaces (helicoids) are the most widely used in practice. In turn, they can be developable and non-developable. The former have a simple analytical description, but require special equipment for their manufacture. There is no exact scan for them, and an approximate one requires plastic deformation and metal redistribution. For developable surfaces, an exact develop can be constructed based on the constancy of the area, line lengths and angles between them, but this requires a complex mathematical description using differential geometry. The production of helical surfaces from a flat workpiece is accomplished by simply bending it, similar to folding a sheet of paper into a cylindrical surface. In this case, plastic deformation is minimal and is due to the thickness of the sheet material.

its formation is violated. It is possible to increase the angle β , so that a certain part of the surface can be constructed downwards, but this increases the distance between the seam of the main and support surfaces on the shaft, which leads to a decrease in the useful volume between turns.

In the work of S. Pylypaka *et al.* (2024b) proposed a helical sweeping surface of constant pitch to be used as a working body of a helical knife of an agricultural implement. The given helical line is the cutting edge. Straight lines pass through it, the inclination of which is chosen to reduce the resistance of the working body to entering the material. The main difference between the surface design in this and the proposed work is that the surface of the working body has a constant pitch and the back edge is also a helical line of constant pitch. This is a special case that can be obtained from dependence (13) of our work when $b=0$. In this case, $z'=a$, $z''=0$ and equation (10) will describe a helical line of constant pitch.

E. Güler & Y. Yayli (2023) and E. Güler & N.C. Turgay (2024) investigated the geometric isometries of helical surfaces in four-dimensional and five-dimensional Euclidean space. They analysed the properties and symmetry of such surfaces using mathematical methods of their

description and classification. However, the authors did not focus on the practical application or design of such surfaces, unlike the current study.

Numerous studies have been conducted on the design of non-rollable surfaces. A. Bankova *et al.* (2024) proposed a method for develop of non-developable surfaces from sheet material, which can be used in the production of complex structures. L. Zawallich & R. Pajarola (2024) considered a mesh approximation of non-developable surfaces, which allows simplifying their geometric model and facilitating the unwrapping process. These studies highlighted the importance of accurate methods for designing such surfaces, which is critical for manufacturing processes.

W. Zhang *et al.* (2024) investigated the process of manufacturing helical surfaces by milling. They focused on the effect of the machining process on energy consumption and the quality of the machined surface. The disadvantage of this approach was the high energy consumption, which requires further process optimisation. In addition, an alternative method of manufacturing screw surfaces, such as bending, was considered by A. Kumar *et al.* (2024). The authors noted that the develop of non-developable surfaces can only be approximate, and their bending into the desired shape significantly increases the energy intensity of the process. Thus, these studies have shown that further improvements in the manufacturing of screw surfaces are needed to reduce costs and increase efficiency.

Scientists V. Tarelnyk *et al.* (2019a; 2019b) studied surface plastic deformations and their impact on the microgeometry, structure, wear resistance and efficiency of coatings. The studies showed that the use of combined surface treatment methods improves the performance of parts. However, the authors did not take into account the impact of surface geometry on such indicators at the design stage, which opens up opportunities for further research in this area.

The question of the construction of developable surfaces was addressed by A.S.M. Kamarudzaman & M.Y. Misro (2024), where the authors studied the develop of the quintic trigonometric Bezier surface. T.G. Nelson *et al.* (2019) proposed approaches to the design of developable surfaces and detailed the areas of their possible application, in particular in robotics, the creation of compact devices and adaptive structures. F. Tash & R. Ziatdinov (2023) considered the developable linear surfaces formed by using the curvature axis of the curve. They investigated the geometric properties of such surfaces and proposed methods for their construction.

In general, a considerable amount of research has been aimed at studying the properties and methods of constructing helical and developable surfaces. However, many works focus only on theoretical aspects, without considering practical applications, unlike the current study.

CONCLUSIONS

A method for constructing a developable surface of the same slope of the constituent elements that passes through a given cylindrical line is developed. The task of the work

was to find a set of rectilinear surface components that would form a developable surface. In addition, all of the generating surfaces must have the same angle of inclination to the horizontal plane. By setting the angles of inclination to different constant values, a set of reamer surfaces passing through a given cylindrical line can be obtained. To solve this problem, a geometric model of the formation of a developable surface was proposed. It consisted of constructing a one-parameter set of cones with a given angle of inclination of their generators to the horizontal plane and a vertex on a given cylindrical curve. The developable surface of such a set of cones is the developable surface. The mathematical implementation of the proposed model consisted in finding the curve of the section of the develop by the horizontal plane. In this plane, a one-parameter set of circles is formed – the sections of cones. The radius of each circle depends on the distance from the horizontal plane to the vertex of the cone, which is located on a given cylindrical line. Since this height is known, the radius of the bases of all cones are known. This circumstance made it possible to find the circumscribing lines of the set of circles in the horizontal plane with their points of contact. The intersection of the point of contact of a particular cone with its vertex determines the rectilinear product of the surface. The parametric equations of the surface and its back edge are obtained. The equations allow us to obtain a surface compartment located between two coaxial cylinders. This is made possible by the fact that one independent variable of the surface equations is the distance from its axis to points on it. At a constant value of this parameter, a bounding cylindrical line of a given radius is formed on the surface. A surface cannot be constructed along the entire length of a given cylindrical line, since a given angle of inclination of its rectilinear components in a certain section of the curve will contradict the law of its formation. Mathematically, this limitation is due to the value of the root expression included in the surface equations, since this expression cannot be negative. The direction of further research should be the construction of a scan of the surface compartment bounded by two coaxial cylinders. For helical surfaces with a constant pitch, such compartments are flat figures in the form of a ring, the bounding radius of which are determined by the formulas. If the pitch is variable, the bounding curves are spiral curves, which require special algorithms to be developed.

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Андрій Несвідомін

Кандидат технічних наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0000-0002-9227-4652>

Сергій Пилипака

Доктор технічних наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0000-0002-1496-4615>

Тетяна Воліна

Кандидат технічних наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0000-0001-8610-2208>

Юрій Штика

Кандидат педагогічних наук, доцент
Сумський державний педагогічний університет імені А.С. Макаренка
40002, вул. Роменська, 87, м. Суми, Україна
<https://orcid.org/0009-0002-5370-6739>

Ірина Рибенко

Старший викладач
Сумський національний аграрний університет
40000, вул. Герасима Кондратьєва, 160, м. Суми, Україна
<https://orcid.org/0000-0001-7795-1689>

**Оптимізація моделі розгортної поверхні,
яка проходить через гвинтову лінію змінного кроку**

Анотація. Недостатнє врахування розгортності гвинтових поверхонь в інженерній практиці ускладнює їх виготовлення та конструювання, особливо для поверхонь змінного кроку. Метою статті була розробка алгоритму конструювання гвинтової поверхні змінного кроку та його математична реалізація. З цією метою були задіяні методи диференціальної геометрії кривих ліній і поверхонь, а також середовище програмного продукту для обчислень, аналізу даних, візуалізації та розробки алгоритмів MatLab для побудови поверхонь за отриманими результатами. Основою для побудови поверхні взято гвинтову лінію змінного кроку, який може бути заданий різними залежностями. Задача полягала в тому, щоб через цю гвинтову лінію із вертикальною віссю провести множину прямолінійних твірних поверхні за умови, щоб вона була розгортною. Додаткова умова – ці твірні мають бути нахилені під сталим кутом до горизонтальної площини, тобто розгортна поверхня має бути поверхнею однакового нахилу твірних. Зазвичай розгортну поверхню задають просторовою кривою – ребром звороту. Множина прямолінійних дотичних до ребра звороту утворює розгортну поверхню. Однак у практичних задачах важливо забезпечити проходження розгортної поверхні через задану криву, наприклад, гвинтову лінію. Встановлено, що через задану гвинтову лінію можна провести множину розгортних поверхонь однакового нахилу твірних із різними заданими кутами. Доведено, легко отримати відсік поверхні, обмежений двома співвісними циліндрами, на одному із яких розташована задана гвинтова лінія. Результати дослідження можуть бути використані для покращення технологій виготовлення шнеків у сільському господарстві, харчовій, гірничодобувній та будівельній галузях

Ключові слова: прямолінійні твірні; напрямні косинуси; поверхня укусу; обвідна крива; шнек

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Mykola Zablodskyi*

Doctor of Technical Sciences, Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0001-8889-8158>

Denys Babak

Postgraduate Student
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0009-0000-8970-8598>

Simulation of fluid spraying processes in a device for automatic control of anaerobic fermentation process parameters in biogas reactors

Abstract. The relevance of the study is justified by the rapid development of biogas technologies, which requires continuous improvement of methods and equipment to increase efficiency and ensure optimal productivity of the biogas and biomethane production process. The aim of this research was to improve and optimise devices for automatic control of anaerobic fermentation process parameters in biogas reactors. Methods of mathematical modelling of the 3D model in the Ansys Fluent environment, as well as methods of experimental studies to determine the spray spectrum of nozzles, jet distribution and the shape of the fluid spray cone were used. A constructive scheme of the device for automatic control of the parameters of the anaerobic fermentation process in biogas reactors, a mathematical model of the process of fluid spraying in the sensor cleaning system, which used equations describing the evolution of the kinetic energy of turbulence and the frequency of turbulence, are proposed. An automatic recorder capable of measuring voltage, current, and pressure with a frequency of about 120 measurements per second was created, which insures a high-precision removal of the load characteristics in the fluid supply system. Based on the results of modelling and experimental studies, the patterns of jet distribution and the shape of the fluid spray cone depending on the change in the diameters of the spray nozzles, were established. The simulation results demonstrated the high accuracy and reliability of the mathematical model, which was an important prerequisite for further complex simulation and optimisation. This study makes a significant contribution to the development of more efficient methods and means of automatic control of the parameters of the anaerobic fermentation process in biogas reactors, contributing to an increase in the productivity of the biogas production process

Keywords: pump load characteristic; Ansys Fluent; spray nozzle optimisation; physical model; fluid flow lines; turbulence effects

INTRODUCTION

The development of new technologies in the field of anaerobic fermentation in biogas reactors requires continuous improvement and optimisation of the use of devices for automatic control of process parameters. For example,

if the fermentation temperature is very low or fluctuates rapidly, it can reduce the efficiency and methane content of biogas (Shao *et al.*, 2021). In the work by G. Sudiartha *et al.* (2023), an in-depth comparison of the impact of

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*Corresponding author



temperature shifts on microbial communities and biogas production was conducted, while A.C. Ibeaja *et al.* (2023) wrote that overall temperature stability helps maximise biogas production.

The regulation of microbial intracellular enzyme activity largely depends on temperature, and this, in turn, affects the metabolic activity of bacteria and the efficiency of anaerobic fermentation. W. Li *et al.* (2017) proved that changes in microbial metabolism or community dynamics also influence the functioning of anaerobic fermentation systems. An important step to create the required temperature conditions in biogas reactors is CFD analysis of heat exchanger model designs using ANSYS Fluent and appropriate control of temperature distribution and gradient (Kishan *et al.*, 2020).

The pH level should be maintained within certain limits, such as 6.8 to 7.2, to maximise microbial activity, especially methanogens, which are crucial for methane production (Lima *et al.*, 2023). Conversely, according to A. Cerón-Vivas *et al.* (2019), increasing the pH above 7.5 can decrease biogas yield.

Anaerobic fermentation processes, as investigated by scientists O.A. Aworanti *et al.* (2023), face operational difficulties such as complexity of substrate structure and characteristics, low productivity, inefficient biodegradability, and low stability. Therefore, to ensure optimal productivity of the biogas and biomethane production process, a more thorough assessment of the current state and available strategies is needed. In addition, for different applications of biogas/biomethane, it is advisable to select the appropriate biomass preprocessing technology before biogas production.

In this context, the issue of efficiency and reliability of measuring devices capable of operating in aggressive environments and various rheological properties of water substrates is particularly important. The use of measuring devices requires periodic cleaning and calibration of a significant number of sensors located in the working volume of biogas reactors. Therefore, it is important to study the process of spraying cleaning fluid and selecting the optimal characteristics of electromechanical fluid supply units and the location of nozzles in the device for automatic control of anaerobic fermentation process parameters in biogas reactors. M.A. Enache *et al.* (2012) noted that the overall productivity and reliability of the device would depend on the accuracy of calculating of the dynamic mode characteristics for low-power DC motors, which were the main electromechanical units of the fluid supply. There are known results of developing a program based on numerical calculation methods that allows solving integro-differential equations with variable coefficients by the Runge-Kutta method of the fourth order and allows establishing a preliminary determination of the dynamic mode behaviour of low-power DC motors with high accuracy. In addition, the results of the practical developments of M.A. Kovalenko & O.O. Samoilenko (2019), devoted to the creation of an experimental device for studying the parameters and characteristics of low-power DC motors, are published. Based on

the results, a schematic diagram of testing these machines based on a microcontroller with the usage of modern highly sensitive sensors has been developed.

However, there is no systematic information on the design of devices for automatic control of anaerobic fermentation process parameters in biogas reactors, and therefore hydrodynamic analysis of fluid flow can only be conducted in comparison with related technological processes of spraying. Previous studies by M.H. Sadafi *et al.* (2016) had shown a significant impact of nozzle location, for example, on cooling efficiency, which confirms the importance of optimal design of these elements. The study by C. Yue *et al.* (2013) was aimed at analysing the hydrodynamic characteristics of a spherical underwater robot with three possible motions. The ANSYS Fluent software was used for hydrodynamic analysis of the three models and comparison of the simulation results with theoretical values of the drag coefficient, velocity vector, and pressure contours.

B. Monachan *et al.* (2019) investigated the behaviour of two-phase flow, which is important for various engineering applications. The authors used a volumetric multiphase fluid flow model in ANSYS Fluent to simulate two-phase air-water flow and focused on predicting stratified laminar flow. They studied the change in the volume fraction of air and water, mass flow rate, and pressure drop over time. Z. Liu *et al.* (2019) studied the spraying properties and rules of nozzle variation with different hole diameters at different atomisation pressures. The study used ANSYS Fluent software to analyse the relationship between average droplet size and spray pressure, as well as the dust suppression efficiency of different nozzle hole diameters.

Researches M. Juraeva *et al.* (2019) optimised a nozzle for a water jet loom using a computational approach. The efficiency of the nozzle was measured in terms of water resistance, which is crucial for woof insertion in water jet looms. The incompressible Navier-Stokes fluid equations with the standard k-epsilon turbulence model were used to simulate the fluid flow, and the ANSYS Fluent software was used to calculate the flow. Geometrical parameters were optimised using the design of experiments (DOE) method using Minitab software. M. Gong *et al.* (2016) performed simulations of gas-liquid flows in pipes of various scales. Based on Frank's model, the emphasis is on the wall-to-wall lubrication force action distance. After modifications, the new model is used to simulate the gas-liquid flow in a transient two-phase flow apparatus with a multiphase circuit using the commercial software ANSYS Fluent.

Mathematical modelling was used in the study of the uniformity of fluid distribution during spraying in agriculture. E. Musiu *et al.* (2019) presented a mathematical model that is based on computational fluid dynamics (CFD) and showed that the flow rate affects the droplet size distribution. Models based on computational fluid dynamics are also used to predict and evaluate spray drift (Wang *et al.*, 2022). The use of the principle of maximum entropy, the model of linearised atomisation of the instability layer, and simulation of computational fluid dynamics should

be considered promising (Renaudo *et al.*, 2022). There is a need for further work in order to achieve compliance of mathematical models with real values of fluid distribution during spraying.

The purpose of this study was simulation and experimental determination of the optimal parameters of the fluid spraying process when cleaning the sensors of the device for automatic control of the parameters of the anaerobic fermentation process in the biogas reactor.

MATERIALS AND METHODS

The research was conducted at the Department of Electrical Engineering, Electromechanics and Electrical Technologies of the National University of Life and Environmental Sciences of Ukraine during 2023-2024. The object of simulation and experimental research was a device for automatic control of the parameters of the anaerobic fermentation process in biogas reactors, the general view of which was presented in Figure 1a.

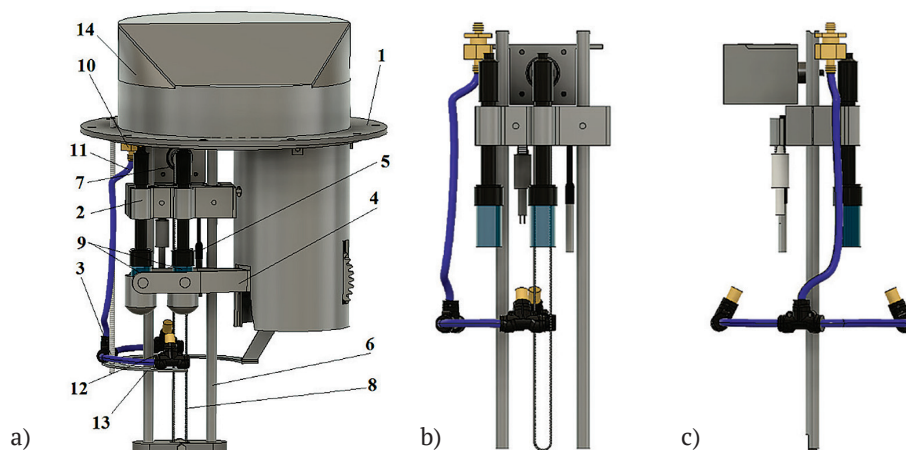


Figure 1. Device for automatic control of anaerobic fermentation process parameters in biogas reactors

Note: a) general view of the device, b) simplified model, XY plane projection, c) simplified model, XZ plane projection

Source: compiled by the authors

To optimise the time of mathematical simulation, a simplified model was used, the projections of which are shown in Figure 1b and Figure 1c, respectively. This model was used for mathematical simulation in the Ansys Fluent environment of the distribution of jets, the characteristics of the shape of the cone of the sprayed fluid depending on the change in the diameters of the spray nozzles.

The simulation was performed for atomisers with a nozzle diameter varying from 0.2 mm to 1 mm with an interval of 0.2 mm. In order to clarify the choice of the optimal atomiser, simulation was additionally carried out detailing the diameters of the nozzles with an interval of 0.1 mm. This approach provided a comprehensive view of the interaction of device parameters, taking into account various conditions and variants of atomiser designs.

The device for automatic control of parameters (Fig. 1a) contained a mounting flange 1, a movable carriage assembly 2, a cleaning system 3, a moving system of protective caps and calibration containers 4, and a calibration liquid supply unit 5. The movable carriage assembly 2 contains linear guides 6, a stepper motor with a toothed pulley 7, a movement belt 8 and sensors 9, which are fixed on a movable carriage. The cleaning system includes a pump 10, a pipeline 11 for supplying water and sprinklers 12 located on a fixed arc-shaped plate 13. Communication equipment, a power supply and a control device in the form of an automatic operation controller (not shown) are located in an isothermal container 14.

To determine the flow rate used in the simulation, the volume flow formula, which allows you to accurately calculate the speed of the liquid passing through the system per unit of time, was used:

$$Q = V \times S \times \cos \theta, \quad (1)$$

where: V is the average flow velocity in the cross-section; S is the cross-sectional surface of the flow; θ is the angle between the flow direction and the normal to the cross-sectional surface.

The flow rate was calculated for a specific pump with factory parameters: voltage – 9-14 V, current – 5A, flow – 5 l/min, pressure – 6.8 bar. The flow velocity used in the simulation was 0.0353 m/s. The adopted parameters ensure adequate reproduction of boundary conditions and turbulent effects, which is important for obtaining reliable results during mathematical modelling in Ansys Fluent.

The modelling domain had a rectangular shape with the dimensions shown in the computational diagram (Fig. 2a). This domain defined the space in which the hydrodynamic processes were modelled. The mesh of the modelling domain (Fig. 2b) had an average of 330,000 nodes and 1,760,000 elements (surfaces). The simulation environment consisted of water and air. The input condition for both phases was taken as the input velocity. In the specified area, the initial water velocity at the start of the simulation was set to 0.0353 m/s.

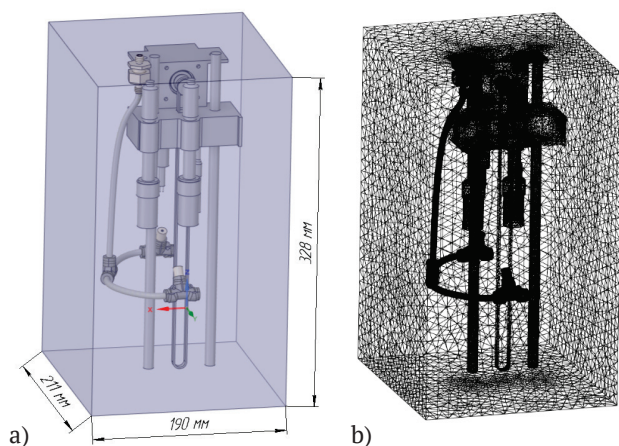


Figure 2. Modelling area

Note: a) calculation scheme; b) grid

Source: compiled by the authors

At the outlet of the system, the initial boundary conditions are used, which are given in the form of pressure. The working pressure is assumed to be 0 bar during the flow analysis, which allows to exclude the factor of pumping water to the outside. The k - ω model is used to account for turbulent effects. This model provides an opportunity to adequately reflect turbulent structures in the system and their influence on hydrodynamic processes (Monahan *et al.*, 2019).

When using the k - ω model in the ANSYS Fluent software package, equations that describe the evolution of the turbulence kinetic energy k and the turbulence frequency ω are used. The main equations of this model are as follows:

1. The equation for the kinetic energy of turbulence k :

$$\frac{\partial(pk)}{\partial t} + \frac{\partial(pk u_i)}{\partial x_i} = P_k - \beta^* p k \omega + \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\sigma_k \mu_t}{\rho} \right) \frac{\partial k}{\partial x_i} \right], \quad (2)$$

2. The equation for the turbulence frequency ω :

$$\begin{aligned} \frac{\partial(p\omega)}{\partial t} + \frac{\partial(p\omega u_i)}{\partial x_i} = & \alpha \frac{\omega}{k} P_k - \beta \rho \omega^2 + \\ & + \frac{\partial}{\partial x_i} \left[\left(\mu + \frac{\sigma_\omega \mu_t}{\rho} \right) \frac{\partial \omega}{\partial x_i} \right] + 2(1 - F_1) \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_i} \frac{\partial \omega}{\partial x_i}, \end{aligned} \quad (3)$$

where: ρ is the density of liquid or gas (kg/m^3); u_i – velocity components in the i direction (m/s); μ_t – dynamic viscosity of liquid or gas ($\text{Pa}\cdot\text{s}$); β^* – turbulent viscosity ($\text{Pa}\cdot\text{s}$), is the empirical constant of the k - ω model (dimensionless), usually equal to 0.09; α is the empirical constant of the k - ω model (dimensionless), usually equal to 5/9; β is the empirical constant of the k - ω model (dimensionless), usually equal to 0.075; σ_k is the empirical constant of the k - ω model, which affects the diffusion of k (dimensionless), usually equal to 2.0; σ_ω is the empirical constant of the k - ω model, which affects the diffusion of $\sigma_{\omega 2}$ (dimensionless), usually equal to 2.0; is an additional empirical constant for the combined model (dimensionless); F_1 is a blending function used to combine the k - ω model with other models

(for example, with k - ε in the SST model) (dimensionless). This function determines what part of the combined model is used in a particular flow region. Turbulent viscosity is calculated as:

$$\mu_t = \rho \frac{k}{\omega}, \quad (4)$$

where: P_k is the term of the turbulence kinetic energy production that describes how the flow velocity is converted into turbulent kinetic energy. It was calculated as:

$$P_k = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j}. \quad (5)$$

These equations take into account the production, diffusion, and dissipation of turbulent kinetic energy and turbulence frequency, which allows modelling a wide range of turbulent flows with high accuracy. The modelling mode uses a fixed time step. The size of the time step is 0.1 seconds, which ensures the necessary accuracy and detail when modelling dynamic processes in the system. The maximum number of time steps is set to 50, with an iteration (time step) of 40. This allows to achieve an optimal balance between accuracy and speed of calculations, providing a detailed reproduction of flow behaviour.

On the experimental stand (Fig. 3), the loading characteristic of the water pump was determined, the parameters of which were used for modelling.



Figure 3. The structure of the experimental stand for determining the loading characteristics of the water pump

Note: 1 – buffer tank, 2 – pump, 3 – automatic recorder, 4 – power supply unit, 5 – water intake pipe, 6 – water supply pipe to the buffer tank, 7 – connecting adapter, 8 – pressure sensor, 9 – communication cable with the computer, 10 – computer

Source: compiled by the authors

For this purpose, an automatic recorder was created, the scheme of which is shown in Figure 4. The automatic recorder is capable of measuring voltage, current and pressure with a frequency of about 120 measurements per second, which ensures high precise removal of the loading characteristic. Such a high frequency of measurements allows obtaining detailed data necessary for further analysis of pump efficiency.

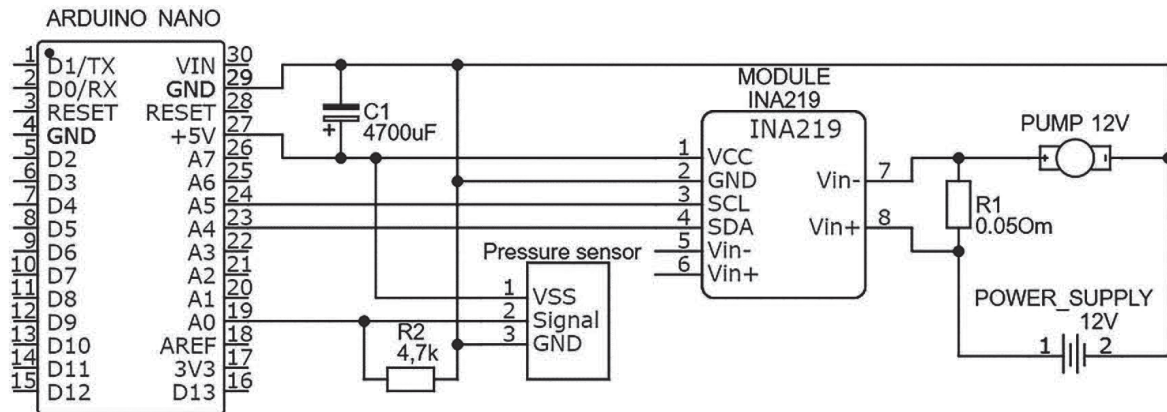


Figure 4. Scheme of the automatic recorder

Source: compiled by the authors

When studying the configuration of the liquid spray cone on a real model of the device, a pressure measurement unit in the nozzle, which is shown in Figure 5, was used.

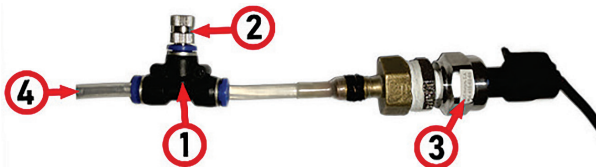


Figure 5. Pressure measurement unit in the nozzle

Note: 1 – connecting adapter, 2 – spray nozzle, 3 – pressure sensor, 4 – water supply tube from the pump

Source: compiled by the authors

To check the accuracy of the mathematical model, the nozzles were first simulated separately from the device. After confirming the adequacy of the mathematical model of hydrodynamic processes for individual nozzles, simulations were carried out on a real model of the device in the presence of at least four sensors.

To obtain data for the further improvement of the device, experiments were conducted to determine the spray spectrum for one nozzle and statistical analysis of the distribution of the amount of liquid that falls on the plane where the sensors can be located. For this experiment, a standard practice was used, which was conducted under laboratory conditions following the method described in P.A. Kluza *et al.* (2019). Tests and measurements were carried out on a corrugated table (Fig. 6) with dimensions of 900×970 mm, which is assembled from 18 plastic corners of 40×40 mm, the distance between the vertexes is 56.6 mm.

The nozzle is located at a height of 0.5 m, and the spray angle in relation to the surface of the corrugated table was approximately 110°. The sprayed liquid fell on the table and flowed down the grooves into 17 plastic containers of the same volume, located consecutively at the same distance from each other. Each measurement using electronic scales DJ-660-0.01 (SPE “Technovagy”, Ukraine) with high accuracy determines the amount of liquid accumulated in

individual containers. Measurements were repeated three times for experiments with different nozzle diameters. Spraying time was 2 minutes for nozzles with diameters of 0.2 and 0.4 mm and 3 minutes for nozzles with diameters of 0.6 and 0.8 mm.



Figure 6. Determination of the spraying spectrum for one nozzle
Source: compiled by the authors

RESULTS AND DISCUSSION

Figure 7 shows the loading characteristic of the pump, which was recorded using an automatic recorder. This made it possible to obtain detailed data on the behaviour of the pump under various loading conditions, which is critically important for accurate mathematical modelling of hydrodynamic processes in the system. The loading characteristic demonstrates that the pump is able to create the necessary pressure, providing a stable and realistic flow of liquid in the system, which confirms its efficiency and compliance with the technical requirements of the simulation.

Figure 8 shows the transient process of setting the pressure in nozzles of different diameters, and Table 1 shows the data of water flow parameters when the nozzle diameter changes.

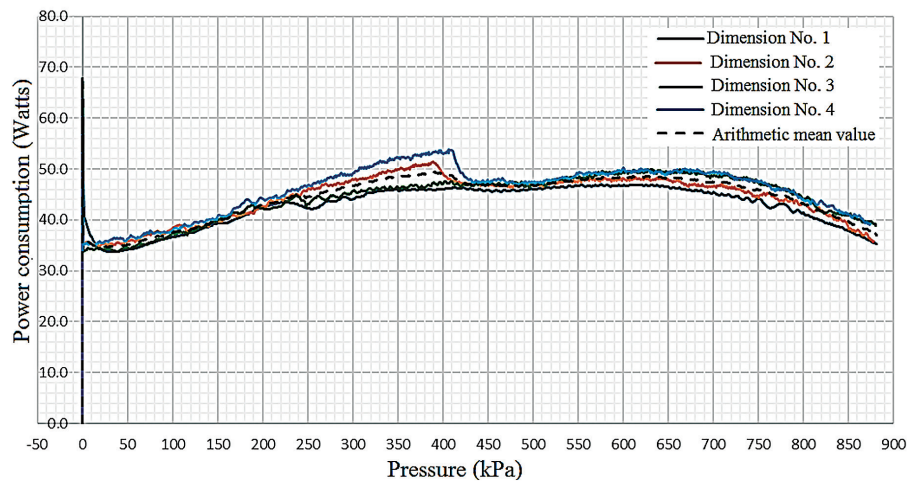


Figure 7. Loading characteristics of the pump

Source: compiled by the authors

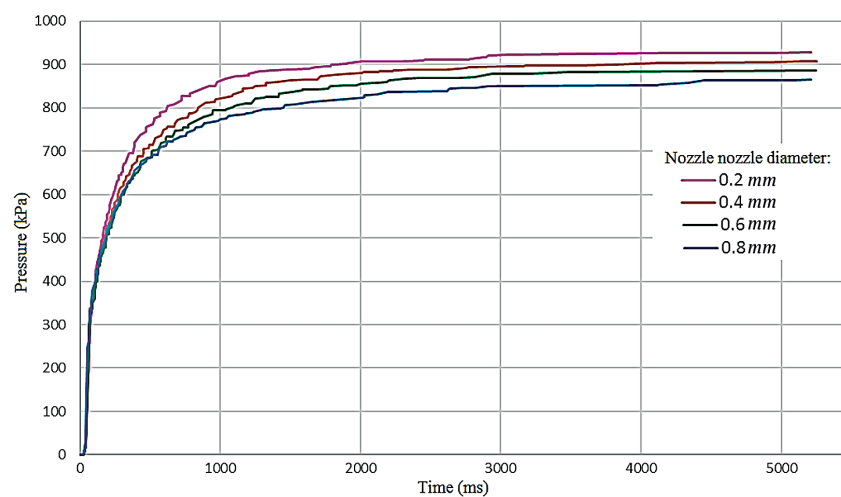


Figure 8. Water pressure in nozzle holes of different diameters

Source: compiled by the authors

Table 1. Dependency of water flow parameters when the nozzle diameter changes

Parameter name	Nozzle diameter, mm			
	0.2	0.4	0.6	0.8
Maximum recorded pressure, kPa	927	907	886	864
Water consumption, hr/min	33.3	89.0	124.0	210.3
The flow rate is determined based on the measured water consumption and the cross-sectional surface of the nozzle, m/s	17.6	13.15	7.72	8.31
The flow rate in the water supply pipeline with a diameter of 4 mm, determined on the basis of the measured water consumption, m/s	0.0441	0.118	0.1644	0.2789
The flow rate in the nozzle simulated at the real flow rate in the pipeline with a diameter of 4 mm, m/s	18.94	14.58	8.58	8.41
Deviation of experimental and simulation results, %	7.0	9.8	10.0	9.9

Source: compiled by the authors

Verification of the accuracy of the mathematical model for the nozzles separately from the device allowed to analyse their free behaviour, providing accurate conditions for checking and establishing the model's compliance with real physical parameters. Figure 9 presents the results of modelling and experimental studies of the distribution of

jets and the shape of the liquid spray cone depending on the change in the diameters of the spray nozzles. The simulation results demonstrate the high accuracy and reliability of the mathematical model, which is an important prerequisite for further complex modelling and optimisation of the entire device as a whole.

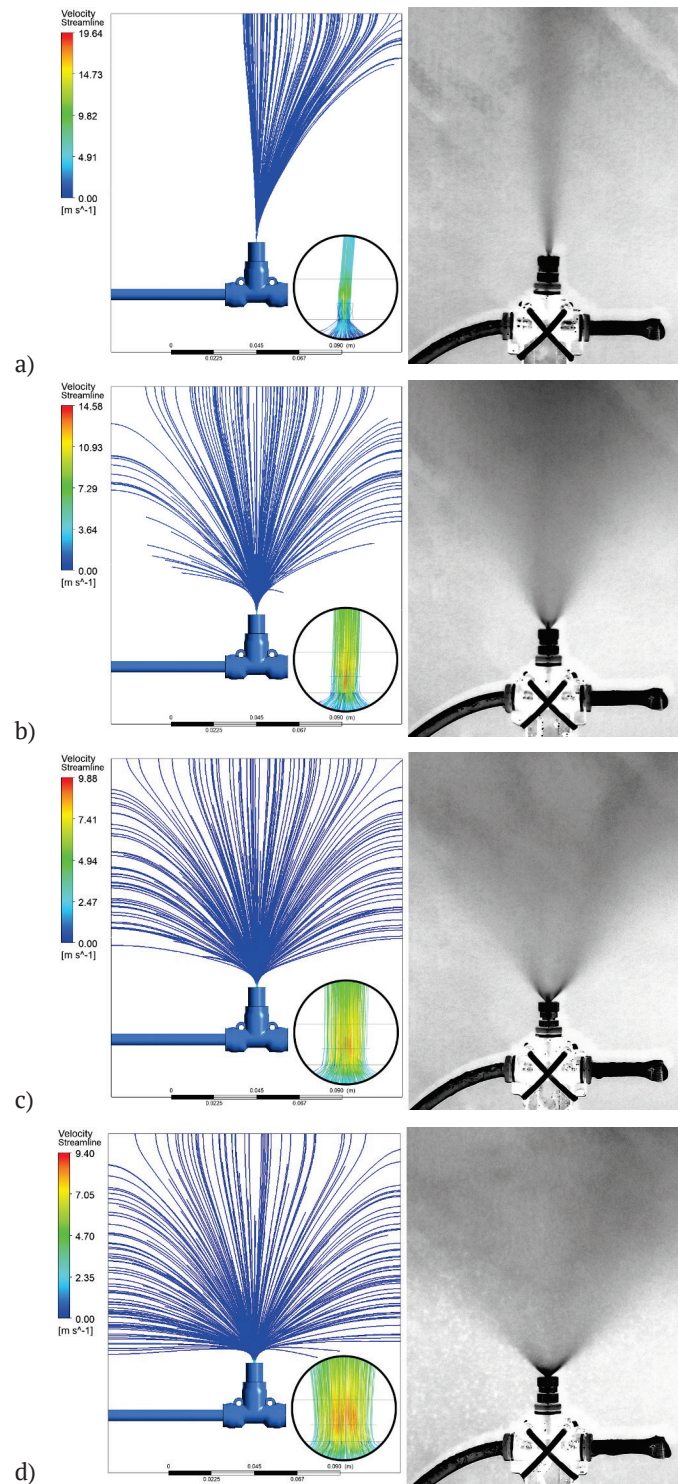


Figure 9. The distribution of jets and the shape of the liquid spray cone depending on the change in the nozzle diameters

Note: the nozzle diameter a) 0.2 mm, b) 0.4 mm, c) 0.6 mm, d) 0.8 mm; on the left – simulation results; on the right – the results of the experiment

Source: compiled by the authors

After confirming the adequacy of the mathematical model of hydrodynamic processes for individual nozzles, simulations were carried out on a real model of the device (Fig. 2) in the presence of at least four sensors. The

simulation results (Fig. 10) include the analysis of the flow lines (Streamline), which gives an idea of the shape of the liquid spray cone in the presence of two nozzles in the device for automatic control of the parameters of the

anaerobic fermentation process in biogas reactors. As can be seen from the results, the optimal diameter of the nozzle is 0.8 mm. The flow lines indicate that the sensors are effectively washed, ensuring their cleaning from dirt. To clarify the results, nozzles with diameters of 0.7 mm and 0.9 mm were additionally modelled. However, as in the previous case, a nozzle with a diameter of 0.8 mm turned out

to be optimal. It provides an optimal wash cone that effectively covers all sensors, ensuring their cleaning.

Mathematical modelling of the 3D model in the Ansys Fluent environment, as in the work by C. Yue *et al.* (2013), made it possible to carry out a detailed analysis of the effect of spray nozzle diameters on the liquid spray cone when washing the sensors in the device.

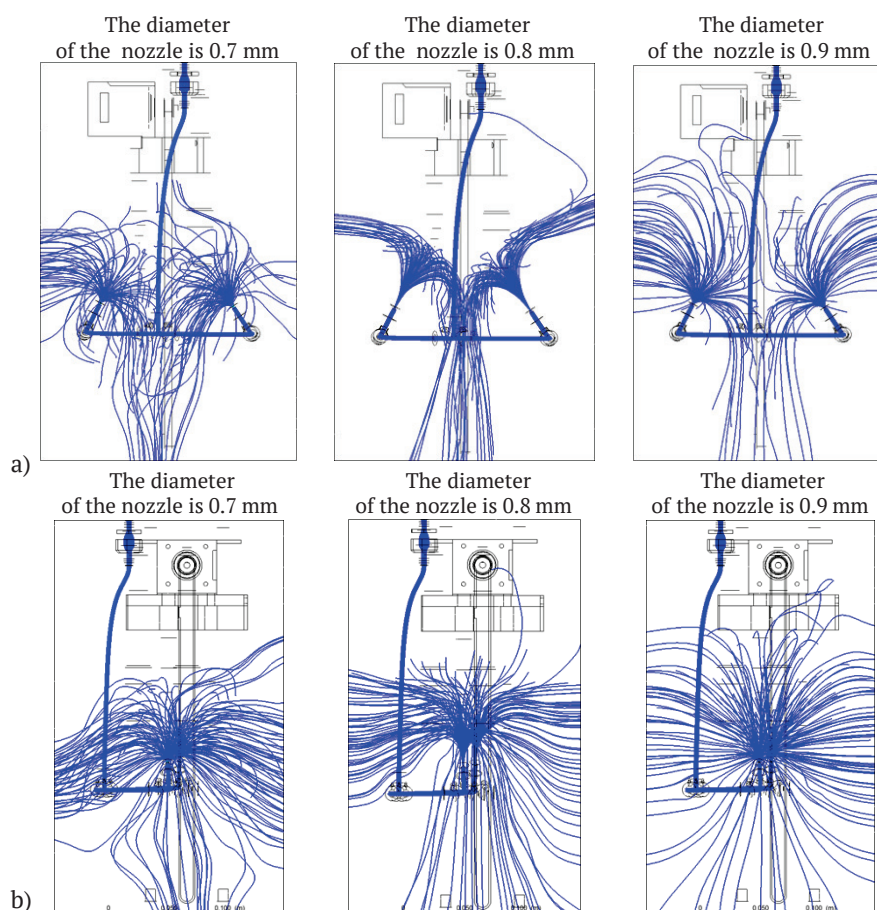


Figure 10. Distribution of flow lines and liquid spray cone in the device for automatic control of anaerobic fermentation process parameters in biogas reactors

Note: a) YZ plane; b) XZ plane

Source: compiled by the authors

Comparison of the simulation results with the experimental values showed that the error was less than 10% despite the threefold increase in leakage pressure compared to the work by C. Yue *et al.* (2013) and the presence of a spectrum of turbulent flows. This indicates the effectiveness of the analysis of hydrodynamic characteristics and the flow field by computational fluid dynamics (CFD) methods.

In current study, the k-omega model of liquid flow was used, where the equations describe the evolution of kinetic energy and turbulence frequency, which provided a smaller error in the analysis of hydrodynamic characteristics compared to experimental data than the standard k-epsilon turbulence model by M. Juraeva *et al.* (2019). Such a

model can be used in both mesophilic and thermophilic regimes compared to Frank's model to predict water-air flow at room temperature in bubble columns in which bubble merging and collapse are not obvious M. Gong *et al.* (2016).

It should be emphasised that the evenness and predictability of the liquid spray distribution are the main characteristics of the cleaning system of the device for automatic control of the parameters of the anaerobic fermentation process in biogas reactors. According to F. Griesang *et al.* (2022), the evenness of liquid distribution across the entire width of the sprayer is influenced, among other factors, by liquid pressure and nozzle type, liquid jet angle, and its symmetry. In current research, it was experimentally determined that even a symmetrical arrangement of two

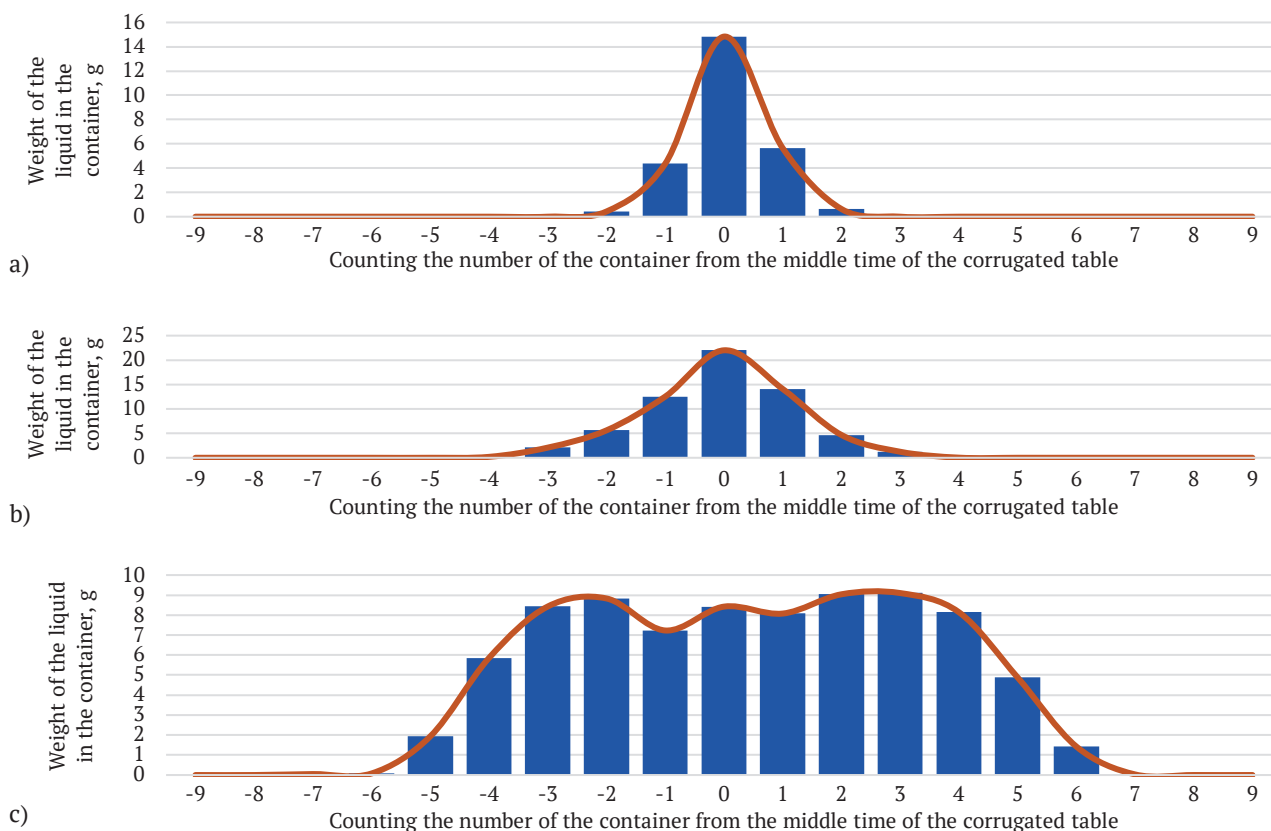
nozzles in the YZ plane provides an optimal washing cone that effectively covers all sensors, ensuring their cleaning.

The results showed that spray pressure and hole diameter significantly affect the spray concentration, and efficiency, including energy efficiency, depends on the purpose of the spray device. For example, in the work by Z. Liu *et al.* (2019), when studying the spray properties and the corresponding rules for changing nozzles with different hole diameters (1.6 mm, 2.0 mm, 2.4 mm) at different spray pressures from 1 MPa to 5.5 MPa, a change in droplet size was observed as the pressure increased, and the evenness of the droplet size distribution reached the optimal level at a pressure of 5 MPa and a hole diameter of 2.4 mm. In our case (Table 1), nozzles of a much smaller diameter (0.2–0.9 mm) were used. When the nozzle diameter increased from 0.2 mm to 0.4 mm, i.e. 4 times, the maximum recorded pressure decreased by no more than 1.1 times, and it amounted 0.864 MPa for the nozzle diameter of 0.8 mm and was sufficient to ensure required degree of evenness of jet distribution in the target zone of sensor washing. A feature of the use of nozzles with a nozzle diameter of 0.6 mm and 0.8 mm is the presence of a spectrum of turbulent flows along chaotic trajectories with mixing in the transverse direction. At the same time, the expansion of the spray cone is observed (Fig. 9).

In general, to evaluate the selection of the number and location of the nozzles for a particular model, it is

possible to use the K-factor, known as the discharge coefficient, obtained from the basic energy equations, which connects the flow rate and static pressure. But, as R.P. Fleming (2016) and P. Croce *et al.* (2020) noted, such a coefficient should be determined experimentally.

Figure 11 shows the results of experimental studies to determine the distribution of the amount of liquid that falls on the plane of the corrugated table. The jet of sprayed liquid has the shape of a cone with characteristics that depend on the design of the nozzle, and the distribution of the amount of liquid that falls on the plane of the corrugated table depends on the diameter of the nozzle. At diameters of 0.2–0.4 mm, a normal distribution was found, whereas at diameters of 0.6–0.8 mm – a liquid distribution that more closely corresponds to the distribution of the spray (Kluza *et al.*, 2019; Cieniawska *et al.*, 2023). It is important to note that with nozzle diameters of 0.6–0.8 mm, the effect of distribution of the liquid amount from one nozzle is the same as when two or three nozzles are located next to each other. At the same time, the variation coefficient, which is the percentage ratio of the mean square deviation to the mean arithmetic value of the characteristic, did not exceed the value of 11.5% for nozzles with a diameter of 0.6–0.8 mm. Accordingly, this confirms the homogeneity of the jet set and the acceptability of such spraying for cleaning the sensors.



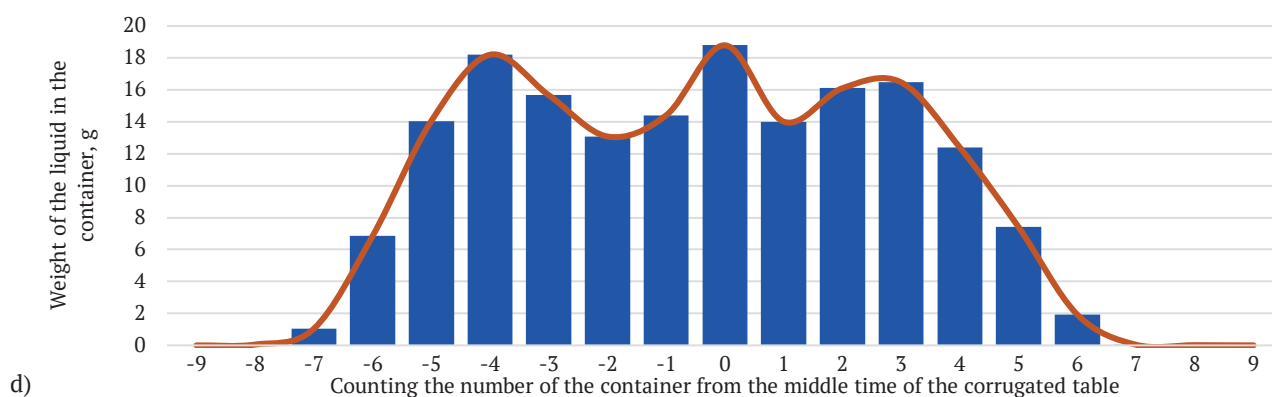


Figure 11. Distribution of the amount of liquid that falls on the plane of the corrugated table

Note: a – Nozzle with a diameter of 0.2 mm; b – Nozzle with a diameter of 0.4 mm; c – Nozzle with a diameter of 0.6 mm; d – Nozzle with a diameter of 0.8 mm

Source: compiled by the authors

It should be emphasised the complexity of the behaviour of two-phase flow and the problems of accurate prediction of flow regimes. In this regard, it will be appropriate to use experimental techniques and non-invasive methods, such as gamma tomography, X-ray methods, capacitive probes and image analysis, to study two-phase flow models.

CONCLUSIONS

The results of the research, carried out using an automated device for controlling the parameters of anaerobic digestion in biogas reactors, highlight the crucial role of optimising structural parameters to ensure effective cleaning of sensors from contamination. A detailed analysis of the effect of nozzle diameters on the shape and area of the spray cone for sensor cleaning, carried out in the Ansys Fluent environment, demonstrated the effectiveness of the developed mathematical model of the liquid spraying process. Comparison of the simulation results with the experimental values showed that the error was less than 10% despite the increase in leakage pressure and the presence of a spectrum of turbulent flows. This indicates the effectiveness of the analysis of hydrodynamic characteristics and the flow field by computational fluid dynamics (CFD) methods.

The model allowed the evaluation of the influence of the nozzle diameter on the uniformity and efficiency of the sensor cleaning, showing that the optimum nozzle diameter is 0.8 mm. This nozzle provides the best balance between cleaning efficiency and cone shape stability. Additional modelling of nozzle diameters of 0.7 mm and 0.9 mm confirmed that deviations from the selected diameter lead to reduced cleaning efficiency or cone shape instability. A feature of the use of nozzles with a nozzle

diameter of 0.6 mm and 0.8 mm is the presence of a spectrum of turbulent flows along chaotic trajectories with mixing in the transverse direction. At the same time, the expansion of the spray cone is observed. The flow lines simulated in Ansys Fluent showed that the distribution of liquid effectively covered the entire sensor plane, ensuring thorough cleaning of the sensors and uninterrupted operation of the device. This demonstrates the feasibility of the chosen design and its accuracy in real operating conditions.

The chosen design parameters improve the performance of the device, reduce measurement errors and increase the reliability of the system. The uniform distribution of the liquid flow, achieved by optimally selected design parameters, significantly reduces the probability of incomplete sensor cleaning and contributes to the operational stability of the device.

The results obtained are of practical significance and serve as a basis for further analysis and improvement of the devices, taking into account variations in the number of sensors, their arrangement schemes and spraying parameters, in order to develop advanced models of automated control systems for similar technological processes.

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CONFLICT OF INTEREST

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Микола Заблодський

Доктор технічних наук, професор
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0000-0001-8889-8158>

Денис Бабак

Аспірант
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0009-0000-8970-8598>

Моделювання процесів розпилення рідини у пристрої для автоматичного контролю параметрів процесу анаеробного бродіння у біогазових реакторах

Анотація. Актуальність дослідження обґрунтована стрімким розвитком біогазових технологій, що потребує постійного вдосконалення методів та обладнання для підвищення ефективності і забезпечення оптимальної продуктивності процесу виробництва біогазу та біометану. Метою цього дослідження було вдосконалення та оптимізація пристроїв для автоматичного контролю параметрів процесу анаеробного бродіння в біогазових реакторах. Використані методи математичного моделювання 3D-моделі в середовищі Ansys Fluent, а також методи експериментальних досліджень по визначенню спектру розпилення форсунок, розподілення струменів та форми конуса розбризкування рідини. Запропоновано конструктивну схему пристрою для автоматичного контролю параметрів процесу анаеробного бродіння в біогазових реакторах, математичну модель процесу розпилення рідини в системі очищення датчиків, в якій застосовуються рівняння, що описують еволюцію кінетичної енергії турбулентності та частоти турбулентності. Створений автоматичний реєстратор, здатний вимірювати напругу, струм та тиск із частотою близько 120 вимірювань на секунду, що забезпечує високоточне зняття навантажувальних характеристик в системі подавання рідин. За результатами моделювання та експериментальних досліджень встановлено закономірності розподілення струменів і форми конуса розбризкування рідини в залежності від зміни діаметрів сопел розпилювачів. Результати моделювання продемонстрували високу точність і надійність математичної моделі, що є важливою передумовою для подальшого комплексного моделювання та оптимізації роботи. Це дослідження робить значний внесок до розробки більш ефективних методів і засобів автоматичного контролю параметрів процесу анаеробного бродіння в біогазових реакторах сприяючи збільшенню продуктивності процесу виробництва біогазу

Ключові слова: навантажувальна характеристика помпи; Ansys Fluent; оптимізація сопла розпилювача; фізична модель; лінії потоку рідини; ефекти турбулентності

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Rysbek Abdylдаev*

PhD in Technical Sciences, Associate Professor
Osh Technological University named after M.M. Adyshev
723503, 81 Isanov Str., Osh, Kyrgyz Republic
<https://orcid.org/0009-0007-2885-965X>

Nurkul Murzakulov

PhD in Technical Sciences, Associate Professor
Osh Technological University named after M.M. Adyshev
723503, 81 Isanov Str., Osh, Kyrgyz Republic
<https://orcid.org/0009-0005-6927-5648>

Almagul Abdullaeva

Postgraduate Student, Associate Professor
Osh Technological University named after M.M. Adyshev
723503, 81 Isanov Str., Osh, Kyrgyz Republic
<https://orcid.org/0009-0001-6999-0490>

Tolgonay Dzholdosheva

PhD in Technical Sciences, Associate Professor
Osh Technological University named after M.M. Adyshev
723503, 81 Isanov Str., Osh, Kyrgyz Republic
<https://orcid.org/0009-0003-1970-2301>

Muhammadsadyk Yslamov

Postgraduate Student, Senior Lecturer
Osh Technological University named after M.M. Adyshev
723503, 81 Isanov Str., Osh, Kyrgyz Republic
<https://orcid.org/0009-0002-5229-1754>

Application of programming methods for control of fluctuations in electric power systems and networks

Abstract. The purpose of this study was to increase the stability of electric power systems to fluctuations through the development and verification of control algorithms based on advanced programming and modelling methods. To solve this problem, algorithms based on proportional-integral-derivative (PID) regulators (including those optimised by evolutionary methods) and artificial neural networks were created and tested. Tests have shown that the classic PID controller can reduce the amplitude of vibrations by an average of 20-30% compared to an uncontrolled system, however, it required fine manual adjustment and was inferior in response speed to sudden load changes. Optimised PID controllers based on genetic algorithms (GA), particle swarm optimisation (PSO), and the firefly algorithm (FA) helped to further reduce the oscillation amplitude (up to 25%, 33%, and 45%, respectively) and accelerated system stabilisation, which significantly increased the reliability of power supply. Of particular interest were neural networks that provided the

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*Corresponding author



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highest adaptability to changing conditions and allowed predicting changes in key parameters (frequency and voltage) with an error of 2-3% in the Mean Absolute Percentage Error (MAPE) indicator. As a result, the network responded to disturbances in a timely manner, reduced the frequency deviation to 0.09 Hz, and reduced the transition time to 3.5 seconds in case of sudden load changes. Thus, the neural network approach has demonstrated the best results in both vibration damping and overall stability of the system. The conducted pilot tests in conditions of intelligent power systems have confirmed the feasibility of integrating the developed algorithms into existing monitoring and control infrastructures. With sufficient computing power and an advanced telemetry system, all the proposed solutions were easily scalable and provided reliable vibration damping even in conditions of active integration of renewable energy sources. Thus, the results of the study confirmed the effectiveness of the developed oscillation control methods and their prospects for further widespread implementation in intelligent power systems

Keywords: integration of renewable energy sources; stability of energy supply; network management algorithms; stability of energy systems; simulation models of power grids; optimisation of management processes; energy security

INTRODUCTION

Electric power systems occupy a key place in the provision of contemporary economy and society, providing vital resources for the functioning of industry, transport, and the domestic sector. With the rapid development of technology and the transition to sustainable energy sources, an integrated approach to infrastructure planning is becoming particularly important. Thus, in the context of engineering calculations and object design, the accuracy of geospatial data plays an important role. As noted by A. Bekturov & A. Chymyrov (2020), evaluating the accuracy of free global digital terrain models and models based on Soviet topographic maps is an important step in planning road routes in Kyrgyzstan. The researchers compared different terrain models, identifying their errors and clarifying the areas of application, which helped to improve the accuracy of engineering calculations. A similar approach to the analysis and consideration of geographical features can also be adapted for the design of energy infrastructure, where the terrain influences the choice of optimal solutions for the placement and connection of energy system facilities.

However, the legislative framework is an equally important element of the integrated development of energy. As indicated by K. Mehta *et al.* (2022), a comprehensive analysis of legal acts in the field of energy in Kyrgyzstan allows creating an effective roadmap for the development of the renewable energy sector. The study examines key legislative norms, identifies barriers and prospects for the introduction of sustainable energy sources, which contributes to the development of strategic solutions for energy transition. This interdisciplinary approach, combining technical, geographical and legal aspects, becomes the foundation for creating reliable and adaptive electric power systems. The nature of fluctuations in electric power grids is determined by a number of factors, including the interaction of generators, changes in consumer loads, and instability of renewable energy sources (Beridze *et al.*, 2023). According to S. Dai & X.-P. Zhang (2022), timely identification of oscillatory processes using measurement methods and big data analysis helps to quickly identify risks to system stability. Further elaboration of strategies for suppressing fluctuations, according to W. Han & A. Stankovich (2022), may be

based on model-predictive control, which allows more flexible damping of power fluctuations in networks with a high proportion of renewable energy sources.

Research by Y. Yang *et al.* (2024) emphasised that the use of genetic algorithms (GA) to suppress broadband fluctuations can increase the stability of power systems even under significant loads. In such studies, various operational scenarios are modelled, including stressful ones, and it is also evaluated to what extent specific solutions (for example, adaptive control algorithms or monitoring tools) are able to reduce the impact of disturbances on the power system. M. Titz *et al.* (2022) showed that machine learning methods can predict the dynamic stability of power grids, which helps to prevent emergencies. It is especially important that the proposed approaches can be adapted to work with distributed energy systems that include a high proportion of renewable energy sources. This makes them particularly relevant in the context of the transition to intelligent energy systems, which are the basis for building sustainable energy for the future.

As indicated by G. Porawagamage *et al.* (2024), machine learning for protection and emergency management of power grids can significantly speed up the response to disturbances in the network – according to the researchers, the response time of protective mechanisms has been reduced by 30%, and the overall stability in case of accidents has increased due to more accurate forecasts. The intellectualisation of fluctuation management in energy systems allows not only optimising the existing infrastructure, but also contributes to the successful integration of new technologies such as renewable energy sources and distributed energy systems (Orynbayev *et al.*, 2024). For example, the study by A. Sabo *et al.* (2024) showed that hybrid methods of computational intelligence integrated with conventional control systems can significantly increase the stability of power grids.

Thus, the application of programming methods to control fluctuations in electric power systems is a promising area that can make a significant contribution to improving the stability and efficiency of power grids. However, despite the successes achieved, scientific and practical tasks remain

unresolved. In particular, a deeper study of the mechanisms of self-tuning and adaptation of algorithms is required in conditions of high uncertainty associated with unstable generation from renewable energy sources. The issues of scalability of intelligent control systems at the level of large distributed networks have not been sufficiently investigated, and the issue of integrating such algorithms into existing hardware and software platforms remains open, considering limitations on telemetry, computing resources, and cybersecurity. In addition, an urgent task is to develop hybrid models capable of combining the advantages of various optimisation methods and machine learning to increase the reliability and adaptability of real-time control. The purpose of the study was to develop and test programming methods for effective control of fluctuations in electric power systems to increase their stability and reliability.

This study provides a detailed analysis of the nature and types of fluctuations in electric power grids, with an emphasis on their causes and impact on the stability of the system. The possibilities of using programming methods to stabilise fluctuations, including the integration of advanced algorithms into power grid management systems, were studied.

MATERIALS AND METHODS

Research planning and time frame. The study was conducted in several stages, each of which had a clear time frame and involved certain actions. First, the key parameters of the experimental bench model of a distributed power system, which included a synchronous generator and a wind turbine to be monitored, were determined, namely: frequency, voltage, and amplitude of oscillations. Based on the technical documentation and the analysis of previous research, the permissible deviations of frequency (± 0.5 Hz) and voltage ($\pm 5\%$ of the nominal value) were indicated, including measurement intervals. The key parameters of the experimental bench model of a distributed power system, which included a synchronous generator and a wind turbine to be monitored, were determined: frequency, voltage, and amplitude of oscillations. Based on the technical documentation, which included the State Standard of Ukraine No. IEC 60038:2015 (2016), as well as the documentation of manufacturers of inverters and electrical machines, reports from energy companies and protocols of Supervisory Control and Data Acquisition (SCADA), the permissible deviations of frequency (± 0.5 Hz) and voltage ($\pm 5\%$ of the nominal value) were established, and measurement intervals were highlighted. For short-term transients lasting up to 10 seconds, high-frequency measurements with a discreteness of 0.01 seconds were planned. Long-term observations, covering periods of several hours, were assigned to assess smooth load changes and the generation of renewable energy sources.

As part of this plan, a bench model was created on which control algorithms were developed and tested: classical proportional-integral-derivative (PID) controllers, their evolutionarily optimised versions (GA, particle

swarm optimisation (PSO), firefly algorithm (FA)), and artificial neural networks. It was planned to conduct a series of experiments under different scenarios of disturbances, including abrupt load changes, shutdowns of generators, and fluctuations in the output power of wind and solar installations. The final stage was the testing of algorithms in the real conditions of the pilot zone, where the standards of intelligent power systems were in effect. The tests stretched over a month and a half to consider both short-term jumps and longer-term changes in the system.

Investigated indicators and simulation scenarios.

In each experiment, the frequency, voltage, and overall response of the system to the disturbance were recorded, and the time of the transient process and the number of repeated oscillations were calculated. These indicators allowed assessing how quickly the system returned to operating mode after a failure occurred. Scenarios reflecting typical situations in power grids were previously formed: abrupt switching of large loads, shutdown of generators (both conventional and those powered by renewable energy sources), and modelling of changeable weather conditions affecting wind and solar generation. In some tests, emergency events related to short circuits on power transmission lines and subsequent disconnection of network nodes were considered. The duration of the experiment was set for each scenario. Short-term modes were studied for 10 seconds to see the primary dynamics of fluctuations and evaluate the instantaneous response of the algorithms. Long-term changes in load and generation were analysed over an interval of up to several hours, which allowed tracking the cumulative effect of many factors on network stability. The data was transferred to a collection and processing system that performed calculations of management performance indicators. Special emphasis was placed on the amplitude and shape of the oscillations, as they characterised the degree of overshoot and the quality of damping.

Methods of processing and interpretation of results. The initial data was systematised in tables, where the values of frequency, voltage, control signals, and load status were recorded for each timestamp. Next, statistical metrics were calculated, which helped to objectively compare the operation of various control algorithms. The Root Mean Square Error (RMSE) was calculated, reflecting the RMS deviation between the actual and calculated values of frequency or voltage. The Mean Absolute Percentage Error (MAPE) indicator was used to evaluate the accuracy of parameter prediction, especially when testing neural networks. These metrics were used in short-term modes (up to 10 seconds) to assess reaction speed and in long-term modes (up to several hours) to identify possible accumulated errors. Stability in case of failures was assessed on an integral 5-point scale, where 1 corresponded to the worst level of stability, and 5 – to the maximum possible. The system's ability to quickly return to operating mode and the absence of repeated large-amplitude oscillations were analysed. The percentage of decrease in the oscillation amplitude was calculated using the equation:

$$\Delta = \frac{A_{\text{base}} - A_{\text{ctrl}}}{A_{\text{base}}} * 100\%, \quad (1)$$

where A_{base} – average oscillation amplitude in the absence of regulation; A_{ctrl} – average oscillation amplitude when using the appropriate algorithm. Accuracy metrics (RMSE, MAPE) provided quantitative estimates of the discrepancy between the observed values of frequency, voltage, and forecast or control signals. The time of the transition process was also determined, indicating the period over which the system reached the permissible deviation limits, and the number of repeated fluctuations, indicating the risk of overshoot. The totality of these indicators was supplemented by an assessment on a 5-point scale. This approach provided a comprehensive view of how successfully the algorithms dampened fluctuations and prevented the network from becoming unstable.

The study used classical and optimised PID controllers. The classic version was manually configured based on preliminary calculations, experiments, and knowledge about the control object. Optimised PID controllers based on evolutionary algorithms (GA, PSO, FA) were trained on historical disturbance data, where the coefficients P, I, and D were systematically changed to minimise overshoot and shorten the transition time. Each evolutionary algorithm went through up to 50-80 iterations (generations), for which the best sets of coefficients were selected. The solutions obtained were tested on a bench model, which helped to identify the regulator with the smallest oscillation amplitude and the shortest transient. To implement neural networks, architectures capable of processing time series of frequency, voltage, and other parameters were selected. The network was trained with a teacher using generation, load, and current oscillation dynamics as input variables, and a forecast of the nearest parameter values and corrective control signals as outputs. The training took place using error backpropagation methods and adaptive optimisation algorithms (Adam, RMSProp). After reaching the target accuracy values (MAPE of the order of 2-3% and RMSE of less than 0.02 Hz), the network was integrated into the control loop. During testing, a prediction horizon of up to 30 seconds was taken into consideration, which allowed responding in a timely manner to sudden changes in network conditions and effectively dampening fluctuations.

Testing solutions in smart power systems. The developed approaches were tested in an intelligent energy system, which involved the active use of digital monitoring systems (SCADA, smart meters), and advanced telemetry and two-way data exchange with consumers. The possibility of integrating algorithms into the Smart Grid pilot zone of one of the Central European energy companies, which has already implemented smart meters and data exchange protocols for operational load management, was considered. The structure of local dispatch systems and ways of interacting with energy generation and storage nodes were analysed. It was evaluated how quickly PID controllers and neural network solutions could adapt to the existing hardware and software platform and respond to typical load

and generation modes for the region. To confirm the effectiveness, laboratory tests and limited field trials were conducted, during which frequency, voltage, and stabilisation time were recorded. In addition to the experience in the European context, the prospects of applying the developed methods in the networks of one of the regions of East Asia, where solar parks and wind turbines were actively developing, were studied. The features of the strong variation of weather factors causing sudden power surges of renewable sources were analysed. The features of the distributed network structure and heterogeneity of telemetry were also considered. The ability of neural networks to self-learn with rapid load changes was tested, and of PID regulators to maintain system stability in conditions of a high proportion of renewable energy sources. Flexible settings of evolutionary algorithms were selected to speed up the search for optimal regulator coefficients.

The final stage included the direct testing of the developed algorithms in a specially equipped test area of an energy company upgrading its network in accordance with Smart Grid standards. The site was equipped with Phasor Measurement Units capable of recording network parameters (voltage, current, shear angles) in real time. A local server was installed that collected and processed incoming data and ran machine learning algorithms. Distributed renewable sources were introduced into the power system, including several solar panels and one wind turbine, and load blocks that simulated real consumers with different consumption profiles. The pilot tests lasted about a month and a half and included simulations of short-term transients (up to 10 seconds) and longer fluctuations (up to several hours). RMSE, MAPE, maximum frequency deviation, total number of repeated oscillations, and transition time were recorded. In parallel, an integral stability assessment was measured on a 5-point scale. The results confirmed that optimised PID controllers and neural networks successfully reduced the amplitude of fluctuations by up to 45% and accelerated system recovery, which increased the reliability of power supply and demonstrated the prospects for further industrial implementation of the developed solutions.

RESULTS

Comparative analysis of oscillation control algorithms

At the first stage of the study, tests of the classic PID controller were carried out in a bench model, including a synchronous generator and a wind turbine. The purpose of this stage was to evaluate the basic efficiency of a standard control algorithm for suppressing fluctuations in an electric power system. Experiments have shown that with a sudden change in load, the classic PID controller reduces the amplitude of frequency fluctuations by an average of 20-30% compared to the uncontrolled mode. The regulator's limited adaptability to rapidly changing conditions was revealed: when changing the parameters of wind generation, there was a need to re-adjust the coefficients P, I, and D to maintain damping efficiency. These results confirmed the limitations of using the classical PID controller in

complex dynamic modes and substantiated the expediency of switching to evolutionarily optimised control algorithms at subsequent stages of the study. Specific criteria were used to evaluate the effectiveness of classical and optimised PID controllers: the average oscillation amplitude, the transition time, and the number of repeated oscillations. The experimental results were calculated using statistical metrics such as RMSE and MAPE. The effectiveness of using optimised control algorithms compared to the classical PID controller has been experimentally confirmed. As part of the research, comparative experiments were conducted with a sudden change in load in the electric power system, the results of which are summarised in a table. For example, the average oscillation amplitude when using a classical PID controller was 0.12 Hz, while the use of PID controllers optimised using GA, POS and FA allowed reducing the amplitude to 0.09 Hz, 0.08 Hz, and 0.07 Hz, respectively. The transition time for the classic controller was 6.5 seconds, while the optimised algorithms demonstrated higher efficiency, reducing the stabilisation time to 4.2 seconds for PID+GA, 4 seconds for PID+PSO, and 3.2 seconds for PID+FA.

Additionally, the stability of the system in case of failures was assessed on a five-point scale, where the classic PID received 2 points, and optimised regulators showed an improvement in this indicator: PID+GA and PID+PSO each scored 3 points, and PID+FA received the highest 4 points. Thus, optimisation of the parameters of the PID controllers using the GA, PSO and FA algorithms helped to significantly reduce the oscillation amplitude by 25%, 33%, and 45%, respectively, compared to the classical PID controller. Experiments were also conducted to control the system using artificial neural networks. These approaches have demonstrated high accuracy in predicting changes in frequency and voltage parameters with an error of 2-3% according to the MAPE indicator. However, the neural network provided the minimum frequency deviation (0.09 Hz during a load surge) and the shortest transition time – about 3.5 seconds.

During the experiments, scenarios of an abrupt increase in consumption, sudden shutdown of generators and unstable weather conditions affecting the operation of distributed renewable energy sources were considered. When simulating an abrupt increase in consumption, it was recorded that the classical PID controller achieved a maximum frequency deviation of up to 0.15 Hz, the transition time was about 7 seconds, and the number of repeated oscillations reached three. The use of an optimised PID controller using FA allowed reducing the maximum deviation to 0.1 Hz, reduce the transition time to 3.8 seconds and the number of repeated oscillations to one, while the use of an

artificial neural network ensured a minimum frequency deviation of 0.09 Hz, the transition time was reduced to 3.5 seconds, and the number of repeated oscillations observed was equal to one. When modelling the scenario of a sudden shutdown of the generator, it was observed that the classical PID controller had a maximum frequency deviation of 0.18 Hz, the stabilisation time was about 6.8 seconds, and the number of repeated oscillations was fixed at two, while the optimised PID controller reduced these values to 0.12 Hz, 4.2 seconds, and one repeated oscillation, respectively; the use of a neural network helped to achieve a maximum deviation of 0.1 Hz, the transition time was reduced to 3.9 seconds, and the number of repeated oscillations remained equal to one. When simulating unstable weather conditions, the classical PID controller recorded the maximum frequency deviation to 0.17 Hz, the transition time was about 7.2 seconds, and the number of repeated oscillations reached two, while the optimised PID controller reduced the maximum deviation to 0.11 Hz, the stabilisation time was reduced to 4.5 seconds, and the number of repeated oscillations was reduced to one. The use of a neural network ensured a minimum frequency deviation of 0.09 Hz, the transition time was 4 seconds, and the number of repeated oscillations was recorded as one. The final test results indicated that the use of a neural network made it possible to significantly improve the dynamic characteristics of the system compared to classical and optimised PID controllers, which resulted in reducing the maximum frequency deviation to 0.09 Hz, reducing repeated oscillations to one and reducing the transition time, which contributed to increasing the stability of the power system in conditions of severe disturbances. Thus, the conducted studies have confirmed the high efficiency of the use of optimised PID controllers and artificial neural networks, which have significantly improved the dynamic characteristics of the electric power system, reduced the amplitude of fluctuations, shortened the transition time, and increased the overall stability and reliability of the network.

The next stage of the study was the development of optimised PID controllers, where the selection of coefficients P, I, and D was performed using evolutionary algorithms. To evaluate the effect of different types of PID controllers on reducing the amplitude and reducing the time of transients, experiments were conducted comparing the effectiveness of the classical and optimised versions of PID controllers under conditions of sudden load changes. The results obtained were summarised in Table 1, which presents key indicators such as the average oscillation amplitude, the transition time, and the overall level of stability in case of failures.

Table 1. Comparison of the efficiency of PID controllers (classic and optimised) with sudden load changes

Indicator	Classic PID	PID+GA	PID+PSO	PID+FA
Average oscillation amplitude, Hz	0.12	0.09	0.08	0.07
Transition period, s	6.5	4.2	4	3.2
Stability in case of failures (points)	2	3	3	4
Percentage of amplitude reduction	-	25%	33%	45%

Source: created by the authors

The results obtained in Table 1 are determined by the specifics of the applied control algorithms and methods for optimising the parameters of PID controllers. The decrease in the average oscillation amplitude when using optimised regulators is explained by a more accurate selection of the coefficients P, I, and D using evolutionary methods such as GA, PSO, and FA. These methods ensure an effective search for optimal parameters, helping to reduce overshoot of the system and increase its stability. The most significant improvements were shown by the FA-optimised PID controller, due to the ability of this algorithm to effectively avoid local extremes and fine-tune the regulator coefficients. This led to a decrease in the average oscillation amplitude to 0.07 Hz and a reduction in the transition time to 3.2 seconds compared to the classical regulator, which had values of 0.12 Hz and 6.5 seconds, respectively. Lower transition times are associated with an increase in the response rate of optimised PID controllers to load changes and an increase in the adaptability of algorithms to dynamic disturbances in the system. The stability of the system in case of failures has also improved due to a more accurate and rapid response of optimised regulators, which is confirmed by an increase in the stability rating on a five-point scale from 2 to 4 points. The percentage of decrease in the oscillation amplitude shows how much the average oscillation amplitude decreased when using an optimised PID controller compared to a classic PID controller. The higher this value, the more effectively the optimised regulator copes with damping vibrations in the system.

Application of neural networks and machine learning methods

To test the approach using artificial neural networks, data was collected on the operating modes of the electric power system in different time periods. Parameters such as the current frequency and its derivatives, the state of the generators (load, excitation current), the parameters of wind and solar generation (power, angular characteristic of inverters), and changes in loads in distribution networks were considered. The structure of the neural networks used included an input layer, several hidden layers, and an output layer that generated control actions such as adjusting the angle of operation of the inverter or changing the excitation current of the generator. The training was

performed using the error backpropagation method, supplemented by adaptive gradient algorithms such as Adam or RMSProp. The results demonstrated high accuracy in predicting changes in frequency and voltage in the power system with a horizon of 30 seconds, with MAPE 2 = 3% relative to the actual values. After completing the training stage, artificial neural networks were integrated into the control loop, where they developed recommendations for correcting control signals in real time. In its study, the neural network considered both the current state of the system and the forecast for the coming seconds. Experiments have shown that this approach can effectively prevent sudden frequency spikes by timely interfering with the operation of generators, and reduce the amplitudes of electromechanical oscillations of generators by considering future changes in load and generation.

Analysis of system stability under various scenarios and loads

For in-depth evaluation, the developed control algorithms, including both improved PID controllers and neural network-based approaches, were tested in a wide range of scenarios. One of the key scenarios was an abrupt increase in consumption, which mimicked the inclusion of a large industrial facility. Another important scenario included a drastic reduction in consumption, for example, in the event of an emergency shutdown of a part of the load. In addition, tests were conducted simulating the shutdown of one of the generators, both conventional and powered by renewable energy sources. Special attention was paid to the conditions of changeable weather, which are especially critical for wind and solar generation, where the output power directly depends on weather factors. The set of scenarios was completed by emergency situations with a short circuit on the power line, requiring a prompt and accurate response from the control system. These scenarios allowed evaluating the effectiveness of algorithms in the conditions of real disturbances typical of advanced electric power systems, and identifying their advantages in ensuring network stability. During the experiments, such indicators as the maximum frequency deviation, the average duration of the transient process, the number of repeated oscillations, and the amplitude of their attenuation were calculated. For clarity, some of the results are presented in Table 2.

Table 2. Comparative results of oscillation control in different scenarios

Script	Control algorithm	Max. frequency deviation, Hz	Transition period, s	Number of repeated oscillations
Abrupt increase in consumption	Classic PID	0.15	7	3
	PID+FA	0.1	3.8	1
	Neural network	0.09	3.5	1
Turning off the generator (conventional)	Classic PID	0.18	6.8	2
	PID+FA	0.12	4.2	1
	Neural network	0.1	3.9	1
Changeable weather conditions (renewable energy sources)	Classic PID	0.17	7.2	2
	PID+FA	0.11	4.5	1
	Neural network	0.09	4	1

Source: compiled by the authors

Table 2 shows that in most cases, the neural network provides the best performance according to all three criteria: minimal frequency deviation, reduced transition time, and reduced number of repeated oscillations. Optimised PID controllers act as an “average” option: they significantly improve performance compared to classic PID, but are slightly inferior to neural networks. The maximum frequency deviation characterised the largest discrepancy from the nominal value, which was observed in the first seconds after the disturbance occurred in the system. This indicator helped to assess the degree of instantaneous reaction of the system to external influences. The duration of the transition process was defined as the time interval during which the frequency returned to the set range of acceptable values, usually ± 0.5 Hz from the nominal value. This parameter reflected the system’s ability to stabilise after a disturbance and ensure stable operation.

A comparison of the results of artificial neural networks with classical PID controllers and their evolutionarily optimised versions has shown that the neural network has higher flexibility in responding to disturbances, especially in complex multifactorial scenarios of load and generation changes. The greatest efficiency was achieved in conditions of distributed generation using renewable energy sources, where it was more difficult for conventional algorithms to adapt to dynamic changes.

Investigation of the possibility of integration into smart energy systems

Advanced concepts of intelligent power systems involve the widespread use of digital monitoring tools, including smart meters, sensors and SCADA systems, decentralised management with active interaction with the load, and a high level of process automation and operational data exchange. To adapt the developed control algorithms to the conditions of the Smart Grid, it was necessary to ensure their compatibility with real-time data exchange protocols, and to consider the significant amount of information coming from a variety of sensors and intelligent devices. In the case of neural networks, special attention was paid to the possibility of scaling architecture and training on large amounts of data, which was implemented using distributed computing clusters and cloud technologies. An analysis of the results showed that with sufficient computing power and advanced telemetry, the proposed solutions can be

relatively easily scaled in intelligent systems, increasing resistance to disturbances, and allowing rapid response to dynamic changes in load and generation. The results demonstrated that machine learning and optimisation algorithms in intelligent networks are capable not only of maintaining stable frequency and voltage parameters, but also of self-learning during system operation. This proved to be especially important in scenarios of network expansion, adding new consumers and sources, which requires an adaptive management approach.

During the integration of machine learning and optimisation algorithms into intelligent networks, some hyperparameters of these algorithms were changed, including the learning rate and the number of layers in neural networks, which improved their ability to self-learn and adjust control signals in real time. Among the main limitations and challenges identified during testing were increased requirements for cybersecurity and data protection, the need to scale algorithms with a significant increase in the number of network nodes, and the risk of reducing control accuracy with high delays and uneven communication quality in decentralised systems. The practical effectiveness of the developed solutions was confirmed during pilot tests conducted in the test area of one of the energy companies upgrading the grid in accordance with Smart Grid standards. Key solutions were implemented at the test site: equipment for measuring voltage and current parameters (Phasor Measurement Units) was installed, a local server was deployed for data processing and implementing machine learning algorithms, and distributed renewable energy sources were connected, including small solar panels and one wind turbine. During the tests, the main performance indicators were determined: the system response time to disturbances (less than 0.1 seconds), the accuracy of peak load forecasting (about 90%), a decrease in the amplitude of frequency and voltage fluctuations (up to 45%), and an overall increase in the reliability of power supply.

The test results showed that the proposed control methods effectively dampened the resulting fluctuations and timely stabilised the parameters of the power grid, preventing transitions to critical states. Thus, the high efficiency and broad prospects of implementing the developed algorithms, including optimised PID controllers and neural networks, into intelligent power systems were confirmed (Table 3).

Table 3. Summary performance indicators of control algorithms when integrated into a Smart Grid

Indicator	Classic PID	PID+FA	Neural network
Reaction time to disturbances, s	0.1	0.08	0.07
Reduction of the oscillation amplitude, %	25%	45%	45%
Accuracy of peak load forecasting, %	80%	85%	90%
Ability to self-study	No	No	Yes
Integration into SCADA/Smart Grid	Limited	Average	High
Computing resource requirements	Low	Average	High
Resilience to dynamic changes	Low	Average	High

Source: compiled by the authors

Analysis of Table 3 suggests that in the framework of pilot tests, the system's response time to disturbances was less than 0.1 seconds, while the use of the classical PID controller was characterised by a reaction time of 0.1 seconds, while the optimised PID controller (using FA) allowed reducing this indicator to 0.08 seconds, and the neural network to 0.07 seconds. A decrease in the amplitude of the oscillations, which reached up to 45%, while the classical method showed a decrease in amplitude by an average of 25%, which indicated a significant advantage of the optimised algorithms and the neural network approach used. The accuracy of peak load forecasting in the integrated system reached about 90% when using a neural network, while the classic PID and optimised PID showed slightly lower rates (80% and 85%, respectively). In addition, only the neural network had the ability to self-learn, which allowed it to adapt to the dynamically changing operating conditions of the power system. When evaluating integration into SCADA/Smart Grid systems using the classical method, limitations were noted, while the optimised PID controller provided an average level of integration, and the neural network provided a high level. A similar pattern was observed when analysing the requirements for computing resources, where the classical method had low requirements, the optimised method had medium requirements, and the neural network approach required significant computing power. Ultimately, resistance to dynamic changes was characterised as low for the classical method, medium for the optimised one, and high when using a neural network. Thus, the analysis of Table 3 confirmed that the best indicators in terms of reaction time, reduction of oscillation amplitude, prediction accuracy and resistance to dynamic changes were provided using neural network algorithms, which corresponds to the data obtained during the tests and indicates the prospects for their implementation in intelligent power systems.

Summarising the results of the study showed that optimised PID controllers and neural networks demonstrate a significant advantage over classical control methods in advanced electric power systems, especially in conditions of dynamic load changes and a high proportion of renewable energy sources. The conducted testing has confirmed the ability of the proposed algorithms to quickly adapt to the real operating conditions of intelligent power systems, including integration into existing monitoring and management infrastructures. An analysis of the pilot test results showed that the proposed methods can stabilise network parameters, reducing the amplitude of fluctuations by up to 45% and reducing the transition time by almost half compared with conventional approaches. Due to the high accuracy of forecasting (about 90%) peak loads and the ability to quickly respond to emergency situations, the implementation of these solutions significantly increases the stability and efficiency of the network.

From the standpoint of integration, the proposed algorithms can be effectively scaled in Smart Grid smart power systems. For successful industrial implementation, it is

recommended to ensure the availability of reliable communication channels, sufficient computing resources, and advanced telemetry systems. Additionally, cybersecurity and data protection issues need to be considered, as smart grids are particularly vulnerable to unauthorised access. Thus, the results of research and testing confirm the prospects of introducing the developed management methods into real industrial operation. Further development involves in-depth study of the self-tuning mechanisms of regulators and improvement of the architecture of neural networks, which will further increase the efficiency and reliability of intelligent power systems.

DISCUSSION

This study examined the problem of managing fluctuations in power systems, based on the growing integration of renewable energy sources, which requires the use of advanced programming methods and adaptive control algorithms. To solve this problem, algorithms based on the classical PID controller, its evolutionarily optimised modifications using GA, PSO, and FA, and neural network approaches based on machine learning methods were developed and tested. The results obtained helped to evaluate the effectiveness of each of the proposed methods in terms of modelling real distributed energy systems characterised by dynamically changing loads and significant participation of renewable energy sources. A comparison of experimental data with the results presented in a number of relevant studies has revealed both similarities and certain differences, which, in turn, helps to better understand the causes and prospects for further development of these management methods.

Experiments have shown that the classic PID controller can reduce the amplitude of vibrations by about 20-30% compared to an uncontrolled system. These results are consistent with data published in the papers by W. Peres & J. Nascimento da Costa (2020) and R. Devarapalli *et al.* (2022), where the stability of the conventional approach in relatively simple systems was noted. However, an experimental protocol focused on simulating distributed power systems with a high proportion of renewable sources has revealed significant limitations of this method. In particular, the transition time in scenarios of sudden load changes was about 6.5-7 seconds, which indicates a relatively slow adaptation of the classical PID controller to rapidly changing system operating conditions. This feature is conditioned by the fact that the classical algorithm is unable to quickly reconfigure itself to dynamic changes, which leads to a deterioration in performance when sudden load surges occur or generators are turned off. These observations are consistent with the results published by L. Zhu *et al.* (2021), which emphasised the non-adaptability of classical methods in the context of multicomponent and dynamically changing systems. To increase the efficiency of oscillation control, it was proposed to use evolutionary algorithms to optimise the coefficients of PID regulators. The use of methods such as GA, PSO, and FA has led to significant improvements in key indicators. In particular, optimisation

using FA resulted in a decrease in the oscillation amplitude to 0.07 Hz and a reduction in the transition time to 3.2 seconds. The results obtained demonstrate the clear advantage of optimised regulators over the classical approach. Comparison of data with the studies by S. Lu *et al.* (2024) and S. Zhang *et al.* (2022) confirmed that evolutionary algorithms allow efficiently performing a global search for optimal parameters, which contributes to a faster restoration of system stability after disturbances. However, it is worth noting that in experiments the indicators turned out to be even more pronounced, which may be due to more detailed modelling of distributed generation and load dynamics. Additionally, an analysis of stability indicators showed that optimised PID controllers demonstrate a smoother transition process and fewer repeated fluctuations, which is especially important when operating power systems where sudden load surges can lead to critical situations.

One of the key areas of research was the use of machine learning methods, in particular artificial neural networks, to control fluctuations. The experimental results showed that the use of neural network algorithms allows achieving minimal frequency deviations (about 0.09 Hz) and significantly reducing the transition time to values of 3.5-3.9 seconds in various scenarios, including an abrupt increase in load, shutdown of generators, and changes in weather conditions affecting the operation of renewable energy sources. These data exceed the figures obtained for both the classical PID controller and its evolutionarily optimised variants. Comparison with the studies by D. Sarkar & T. Prakash (2022) and J. Yang *et al.* (2022) showed that neural network approaches have high flexibility and the ability to self-learn, which allows them to quickly respond to multiple disturbances in the energy system. In the case of an improved neural network architecture, an expanded set of input parameters, and the use of advanced learning methods such as Adam and RMSProp algorithms have ensured the accuracy of predicting system dynamics by 5-10% higher compared to some previous studies. Thus, neural network algorithms not only stabilise the system parameters, but are also able to predict future deviations, which opens up opportunities for timely correction of control signals (Zhanpeisova *et al.*, 2024).

Despite the obvious advantages of neural network methods, their use requires significant computational resources at the learning stage, and the availability of large amounts of high-quality historical data. J. Vives (2022) emphasised the dependence of forecasting accuracy on the size of the training sample and the speed of data processing. In the study, this issue was solved through the use of distributed computing clusters and advanced data pre-processing methods, which allowed ensuring the necessary quality of the training sample and prompt calculations. The experimental results described in this study indicate that the integration of optimised PID controllers and neural network algorithms can provide a high level of stability and adaptability of power systems, especially in conditions of distributed generation, when many factors

simultaneously affect the behaviour of the system. The use of evolutionary algorithms to optimise the parameters of classical regulators allows significantly reducing the amplitude of oscillations and shortening the transition time, which is confirmed by both experimental results and data presented in the works of P.K. Agarwal & C. Kumar (2019) and Y. Wang *et al.* (2022). Neural network algorithms, in turn, have demonstrated high efficiency in managing complex dynamic processes, which is confirmed by L. Vanfretti & X. Bombbois (2024) and K. Aleikish & T. Øyvang (2023). At the same time, experiments showed a tendency for the system to respond more quickly and accurately to sudden load surges due to the expanded architecture of the neural network and higher quality of training data.

The issue of integrating the developed algorithms into the Smart Grid infrastructure is also of interest. The pilot tests have shown that optimised PID controllers and neural network methods can be successfully implemented in real time with advanced monitoring systems such as smart meters, Phasor Measurement Units, and SCADA systems. Comparison of data with the findings of H. Islam *et al.* (2020) and M. Robin *et al.* (2023) showed that the use of advanced control algorithms in the Smart Grid infrastructure allows not only to stabilise the frequency and voltage in the network, but also to predict future disturbances with an accuracy of up to 90%. Such high forecasting accuracy makes it possible to quickly respond to changes in the operating mode of the power system, which is critically important when managing distributed generation and multiple connected consumers. It should be noted that the integration of intelligent control algorithms into Smart Grid systems is accompanied by a number of challenges related to cybersecurity and protection of transmitted data (Sukhodub & Serdechnyi, 2024). In a number of studies, such as the research by Y. Liu & C. Liu (2024), and A. Sundaramurthy *et al.* (2024), emphasised the importance of implementing additional encryption and traffic monitoring mechanisms to protect the infrastructure from unauthorised access. The study also considered the following aspects: the implementation of optimised control algorithms was accompanied by the development of measures to protect information channels, which, despite a slight increase in system response time, improved the overall reliability and security of the power system. Such a compromise between processing speed and security level is acceptable, since the stability and security of the system are of paramount importance in the context of modern digitalisation of energy supply (Panov & Tymchuk, 2023).

A comparative analysis of the experimental results showed that the combined use of evolutionarily optimised PID controllers and neural network algorithms is highly effective. The data demonstrated that the classic PID controller, despite its proven and reliable performance, has limited adaptability and cannot cope with rapid load changes, which leads to an increase in the transition time and a decrease in the stability of the system. Optimisation of the regulator parameters using evolutionary algorithms allows signifi-

cantly reducing the amplitude of fluctuations and accelerating the stabilisation process, but even in this case, the effectiveness of the algorithms is limited by the features of the dynamic conditions of distributed generation (Costanzo *et al.*, 2024). The most outstanding results were achieved using neural network methods, which, due to the ability to self-learn and predict, ensure the smallest frequency deviations and the fastest possible system response. These conclusions were confirmed by W.M. Witharama *et al.* (2024) and S. Yusuf Ibrahim *et al.* (2023), and in experimental data, where the neural network approach demonstrates the ability to adapt to changes 5-10% faster compared to optimised PID controllers. Differences in the results between optimised PID controllers based on different evolutionary algorithms may also be related to the features of algorithmic implementation (Fu *et al.*, 2022; Zhang, 2024). Thus, FA showed better results due to more detailed settings for the local search for optimal parameters, while GA and PSO sometimes faced the problem of getting stuck in local minima. This indicates the need for further research and development of hybrid methods capable of combining the advantages of various approaches to achieve the most stable and adaptive characteristics of the control system.

Thus, the conducted research not only confirms the high efficiency of advanced methods of oscillation control in electric power systems, but also demonstrates the prospects for their integration into the infrastructure of intelligent energy systems. The experimental results showed that the developed algorithms using both evolutionary optimisation methods and neural network approaches are capable of significantly reducing the amplitude of oscillations, reducing the time of transients, and increasing the overall stability of the system under various scenarios of disturbances. The results of this study confirmed the need to move from classical management methods to more advanced approaches using the capabilities of evolutionary algorithms and machine learning. The data obtained indicate the high scalability and adaptability of the developed methods, which makes them promising for practical application in the context of the integration of distributed generation and the implementation of the Smart Grid concept.

CONCLUSIONS

The conducted research was aimed at increasing the stability of electric power systems to fluctuations through the use of advanced programming and optimisation methods. In the course of the study, control algorithms based on

classical and optimised PID controllers, and artificial neural networks, were developed and tested. The parameters of the PID regulators were selected using evolutionary algorithms – GA, PSO, and FA. This reduced the oscillation amplitude to 0.07 Hz and reduced the transition time to 3.2 seconds. However, the classical PID controller provided a decrease in amplitude only to 0.12 Hz, and the transient process lasted about 6.5 seconds.

The use of neural network approaches provided the best results among the tested methods. The MAPE was 2-3%, the maximum frequency deviation during disturbances was no more than 0.09 Hz, and the duration of the transition process was reduced to 3.5 seconds. In addition, the neural network reduced the number of repeated oscillations to one, demonstrating high adaptability to dynamic changes in the operating mode of the power system. The developed algorithms were verified in conditions of intelligent power systems, which included modelling real-world scenarios such as load surges, shutdowns of generators, and unstable generation of renewable energy sources. Moreover, the oscillation amplitude decreased by up to 45%, peak load prediction accuracy reached 90%, and the system response time was less than 0.1 seconds. Due to the use of telemetry, SCADA systems and smart meters, algorithms were integrated into the existing infrastructure without the need for deep modernisation. The possibility of scaling solutions was confirmed, provided sufficient computing power and reliable communication.

Thus, the high efficiency and practical applicability of the proposed oscillation control methods were demonstrated. The results obtained confirmed the feasibility of implementing these methods in advanced distributed power systems with a high proportion of renewable energy sources. Further research is planned to optimise control algorithms, integrate hybrid methods and adapt the developed solutions to more complex power system operating conditions, which will contribute to further improving their stability and reliability.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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Рисбек Абдилдаєв

Кандидат технічних наук, доцент
Ошський технологічний університет імені М.М. Адишева
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка
<https://orcid.org/0009-0007-2885-965X>

Нуркул Мурзакулов

Кандидат технічних наук, професор
Ошський технологічний університет імені М.М. Адишева
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка
<https://orcid.org/0009-0005-6927-5648>

Алмагул Абдуллаєва

Аспірант, доцент
Ошський технологічний університет імені М.М. Адишева
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка
<https://orcid.org/0009-0001-6999-0490>

Толгонай Джолдошева

Кандидат технічних наук, доцент
Ошський технологічний університет імені М.М. Адишева
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка
<https://orcid.org/0009-0003-1970-2301>

Мухаммадсадик Ісламов

Аспірант, старший викладач
Ошський технологічний університет імені М.М. Адишева
723503, вул. Ісанова, 81, м. Ош, Киргизька Республіка
<https://orcid.org/0009-0002-5229-1754>

Застосування методів програмування для керування коливаннями в електроенергетичних системах і мережах

Анотація. Метою цього дослідження було підвищення стійкості електроенергетичних систем до коливань за допомогою розроблення та верифікації алгоритмів керування, заснованих на сучасних методах програмування і моделювання. Для розв'язання цієї задачі було створено і протестовано алгоритми на основі PID-регуляторів (зокрема оптимізованих еволюційними методами) і штучних нейронних мереж. Випробування засвідчили, що класичний PID-регулятор здатний знижувати амплітуду коливань у середньому на 20-30 % порівняно з некерованою системою, однак потребував тонкого ручного налаштування і поступався у швидкості реакції на різкі зміни навантаження. Оптимізовані PID-регулятори на основі генетичних алгоритмів, рою частинок і алгоритму світлячків давали змогу додатково зменшувати амплітуду коливань (до 25 %, 33 % і 45 % відповідно) і прискорювали стабілізацію системи, що значно підвищувало надійність енергопостачання. Особливий інтерес представляли нейронні мережі, що забезпечили найвищу адаптивність до мінливих умов і давали змогу прогнозувати зміну ключових параметрів (частоту і напругу) з помилкою 2-3 % за показником Mean Absolute Percentage Error (MAPE). У результаті мережа своєчасно реагувала на збурення, знижувала відхилення частоти до 0,09 Гц і скорочувала час перехідного процесу до 3,5 секунд у разі різкої зміни навантаження. Таким чином, нейромережевий підхід продемонстрував найкращі результати як щодо демпфірування коливань, так і щодо загальної стабільності системи. Проведені пілотні випробування в умовах інтелектуальних енергосистем підтвердили доцільність інтеграції розроблених алгоритмів в наявну інфраструктуру контролю та управління. За достатньої обчислювальної потужності та розвиненої системи телеметрії всі запропоновані рішення були легко масштабовані та забезпечували надійне демпфірування коливань навіть за умов активної інтеграції поновлюваних джерел енергії. Таким чином, результати дослідження підтвердили ефективність розроблених методів керування коливаннями та їх перспективність для подальшого широкого впровадження в інтелектуальні енергосистеми.

Ключові слова: інтеграція відновлюваних джерел енергії; стабільність енергопостачання; алгоритми керування мережею; стійкість енергосистем; симуляційні моделі енергомереж; оптимізація процесів керування; енергетична безпека

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Vitalii Tsopa

Doctor of Technical Sciences, Professor
International Institute of Management
04116, 10/12 Shulyavska Str., Kyiv, Ukraine
<https://orcid.org/0000-0002-4811-3712>

Tamara Bilko*

PhD in Biological Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0003-3164-3298>

Serhii Cheberyachko

Doctor of Technical Sciences, Professor
Dnipro University of Technology
49005, 19 Dmytro Yavornytskyi Ave., Dnipro, Ukraine
Metinvest Polytechnic Technical University
69008, 80 Pivdenne Highway, Zaporizhzhia, Ukraine
<https://orcid.org/0000-0003-3281-7157>

Oleg Deryugin

PhD in Technical Sciences, Associate Professor
Dnipro University of Technology
49005, 19 Dmytro Yavornytskyi Ave., Dnipro, Ukraine
<https://orcid.org/0000-0002-2456-7664>

Bohdan Hrymalo

Postgraduate Student
Dnipro University of Technology
49005, 19 Dmytro Yavornytskyi Ave., Dnipro, Ukraine
<https://orcid.org/0009-0003-9523-460X>

**Automated software package for selecting transport technology
for grain transportation by road freight transport**

Abstract. The aim of the work was to develop a software package for making a management decision to choose a transport technology for grain transportation by road from a set of alternatives. To achieve this goal, the morphological analysis method was used, which is based on selection of possible solutions for individual parts of the task. A software package for making a management decision from a set of alternatives was proposed, which consisted of four modules and four blocks. It was based on two methods: fuzzy Decision-Making Trial and Evaluation Laboratory (hereinafter – fuzzy Dematel) and gray relational analysis (hereinafter – GRA), which are used to determine the basic indicators and, on their basis, select the transport technology for grain transportation itself. The software package implemented an algorithm of eight

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*Corresponding author



steps: entering groups of indicators, their pairwise analysis, determining basic indicators based on the total matrix of relationships, entering the values of basic and reference indicators of transport technologies for grain transportation and weight coefficients, constructing gray analysis matrices, determining the index of basic indicators relative to target ones achievement. As a result, the best transport technology for grain freight road transportation was selected to meet the target (reference) indicators of the motor transport enterprise according to the following indicators: load transportation tariff; load transportation speed; diesel fuel consumption per 100 km; load volume; transportation distance; transport process energy intensity; time spent on loading and unloading operations; load safety during transportation; carrier reliability; driver satisfaction with working conditions. According to the calculation results, it was noted that the transport technology for grain transportation best meets the target indicators – load road train with dump semi-trailer. The dependences of the transport technology for load transportation basic indicators and motor transport enterprise target indicators were established, which allows improving the algorithm for making management decision to choose an effective transport technology for transportation from a set of alternative ones. The proposed process of selecting the best solution from a set of alternatives can be used in organisations that select the best technology for road load transportation of bulk cargo – grain

Keywords: transport technology; fuzzy Dematel method; gray relational analysis method; target indicators; benchmark indicators; management decisions

INTRODUCTION

Road transport is a key element in providing agro-industrial enterprises with efficient grain transportation. The costs of transport services significantly affect the cost of products and the financial results of enterprises. At the same time, the transport process depends on numerous risks, such as climate change, rising fuel prices, the technical condition of the fleet and personnel shortage. Many enterprises use their own equipment, but its effectiveness is often limited by technical characteristics – wear and tear. To optimise transportation, it is necessary to choose transport technologies that ensure minimal costs, product safety and efficient use of resources. This problem can be solved by developing an automated system for selecting transport technologies using fuzzy logic methods. This will allow to take into account various conditions of the transport process and reduce the impact of uncertainty on decision-making (Vickerman, 2024). Substantiation of delivering goods vehicles models is an important part of the modelling transport process procedure. Existing classical methods can be conditionally divided into two groups: those that take into account the stochastic characteristics of vehicles for delivering goods, and the others include those that do not take into account the stochastic vehicles characteristics (Tsopa *et al.*, 2024).

Several publications are devoted to the development of the first group. The authors of the work X. Hu *et al.* (2019) considered the determination of stochastic parameters of the load delivery process based on the development of a multi-objective software package. It was based on a heuristic-adaptive genetic algorithm, which allows to solve the problem of transportation optimisation. Comparing the results of calculations with experimental data, the paper concluded that the proposed algorithm was effective. However, the authors did not indicate any limitations in the application of the algorithm for forming load transportation schedules. In another work by L. Pečený *et al.* (2020) a cargo delivery planning program based on discrete-event modelling was proposed. For this purpose, load transportation

scenario was developed taking into account the influence of organisational and technical fleet management policies. Additionally, load distribution data between carriers was also taken into account. The authors believed that the proposed approach will reduce the number of delays and failures in cargo timely delivery to customers. However, the use of discrete-event modelling assumes that no changes occur in the transportation system between certain consecutive events, which limits its application in emergency cases. C.B. Gustavo *et al.* (2021) proposed to use multidimensional functions in conjunction with XGBoost (eXtreme Gradient Boosting) to reduce fuel consumption by quarry trucks. The authors believed that using XGBoost could improve the accuracy of fuel consumption monitoring on the route, taking into account the transportation distance, lifting height, and time of one transportation cycle. However, the work did not indicate that works would need to retrain XGBoost due to shortcomings in the collected data, or when data with categorical features were obtained. An interesting solution was proposed by Q. Wang *et al.* (2021), who developed a program to establish dependencies between stochastic vehicle characteristics and truck movement trajectories using a global positioning system based on a model. However, the study itself indicates its drawback, which is related to the problem of real-time data processing.

In the development of the second group, existing studies are devoted to studying the influence of specific vehicle efficiency indicators and route characteristics on the efficiency of the load delivery process. For example, Z. Lyu *et al.* (2022) proposed an adaptive polyloid memetic algorithm (APMA) to improve the efficiency of the load transportation planning process. The algorithm is based on the concept of polyploid, when it is proposed to evaluate the efficiency of transportation based on the objective function analysis, taking into account possible alternative scenarios that differ in minor changes in input parameters (inventory level, operations number, flexibility of supply chain operations, carbon dioxide emissions reduction, etc.). The

program allows, based on the analysis of the objective function, to find the best solution for planning the cargo transportation chain. However, a drawback that requires further research is the processing of a significant number of possible solutions that have minor differences and require additional analysis. M.A. Dulebenets (2021) solved the problem of reducing the load delivery time uncertainty due to possible failures during the cargo reloading (transfer) from one carrier to another in a mixed transportation system. To reduce uncertainty, the authors proposed a software complex built on the identification of opportunity fuzzy chances. It allows you to estimate, based on various input data, the equipment breakdowns probability or loss of time during the unloading-loading process, which affects the actual time of cargo transfer to the other party. Unfortunately, the authors limited themselves only to calculating possible time losses and did not propose solutions for possible compensation of these delays by using a different transportation route. Researchers F. Essghaier *et al.* (2021) proposed to increase the efficiency of load delivery by developing rational work and rest regimes for drivers (RWRs) and implementing them in the transport process. To this end, based on mathematical modelling, two RWR schemes were proposed, which, according to the researchers, will make it possible to increase the daily duration of truck driving up to 10 hours, during any one week. It is indicated that the increased driving duration should be compensated by an equivalent rest time, when replacing a 45-minute break with several breaks lasting at least 15 minutes each. C. Sénquiz-Díaz (2021) concluded that the most effective route planning method is the branch and network method, which allows obtaining a route with the shortest distance for cargo delivery. However, it is not clear how this method allows for the determination of other important indicators: time, fuel consumption. The authors reported that for such tasks, a combination of several calculation methods can be made. I. Skovron *et al.* (2020) and M. Feng & Y. Cheng (2021) solved optimisation problems using the PROMETHEE method to make a decision for fleet selection taking into account various criteria such as efficiency, sustainability, cost, etc. or the cross-data analysis method, which indicates a positive and significant relationship between different factors of the transport process. However, the presented approach has limitations in terms of iterations number with variable indicators of the transport process and requires improvement of existing algorithms.

The presence of many variable parameters in the considered works and the given formalisation of the research conditions do not allow for a qualitative analysis of the obtained results and the development of recommendations that allow using any of the proposed approaches as universal for choosing the optimal (rational) transport technology for transporting goods by vehicles. Therefore, solving the problem of making a management decision to choose a transportation route from a set of alternatives is relevant. Its solution would guarantee the maximum result for a transport company engaged in the delivery of agricultural products.

The purpose of the work was to develop a software package for making a management decision to choose a transport technology for transporting grain by road freight transport from a set of alternatives.

MATERIALS AND METHODS

To achieve the goal, the morphological analysis method was used, which is based on the selection of possible solutions for certain parts of the task (Feng & Cheng, 2021). For this purpose, several morphological typical features (indicators) of grain transportation technologies by road transport (carrying capacity, diesel fuel consumption, loading and unloading time, operating speed, etc.) were identified, which allow to make the necessary management decision. The identified features are presented in the form of tables, the so-called morphological boxes (matrix), which simplified the determination of the most influential on the transportation process.

Further, based on the system analysis, an automated software package was generated for making a management decision on the choice of a transport technology for grain transportation by road from a set of alternatives (Kim & Kim, 2020). It consisted of an initial data module (1), a memory module (2), an information output and visualisation module (3), and a calculation module (4). The calculation module included block 1 for forming a total matrix of pairwise relationships of transport technology certain indicators, block 2 for determining basic indicators and a block for forming a gray analysis matrix, block 3 for processing data on and a block for selecting the best solution from a set of alternative solutions, and block 4 for determining the rating of alternative solutions (Fig. 1).

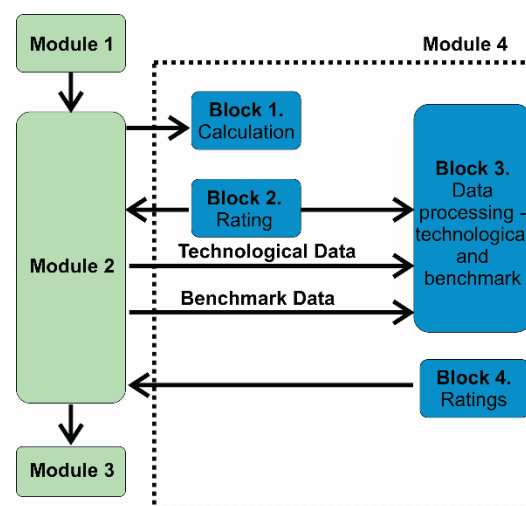


Figure 1. Functional diagram of the software complex
Source: developed by the authors

The software complex contained the following elements: data input/output forms in the form of a modular structure, a multifunctional software tool implemented in the Python programming language, using a data storage library (for example, Tkinter or PyQt), which ensured the

appropriate calculations. The data of the indicator groups were entered by experts through a special window in module 1. Then they were stored in module 2 and, if necessary, transferred to module 4 in block 1 or block 3. Also, the results of determining the basic indicators from block 2 and the results of calculating the best transport technology from block 4 were transferred to module 2. All data stored in module 2 were transferred to module 3 for visualisation.

The software package is based on two methods: the fuzzy Dematel method for determining the basic indicators of transport technology (Bazaluk *et al.*, 2024; Tsopa *et al.*, 2024b) and the gray relational analysis (GRA) method for analysing the set of alternatives (Quan *et al.*, 2018; Lu *et al.*, 2023). At the first stage, an analysis of all indicators of

the transport technology of grain transportation by truck was carried out to determine the basic indicators using the fuzzy Dematel method. At the second stage, the best transport technology of grain transportation was selected using the GRA method.

In theory, gray relational analysis allowed finding the relationship between different transport technologies of grain transportation by truck. When using the gray analysis method, a comparison was made of target (reference) indicators defined by the customer with actual indicators, which allows establishing the degree of similarity and determining the best transport technology of grain transportation by truck. The software complex included 8-Step algorithm (Fig. 2).

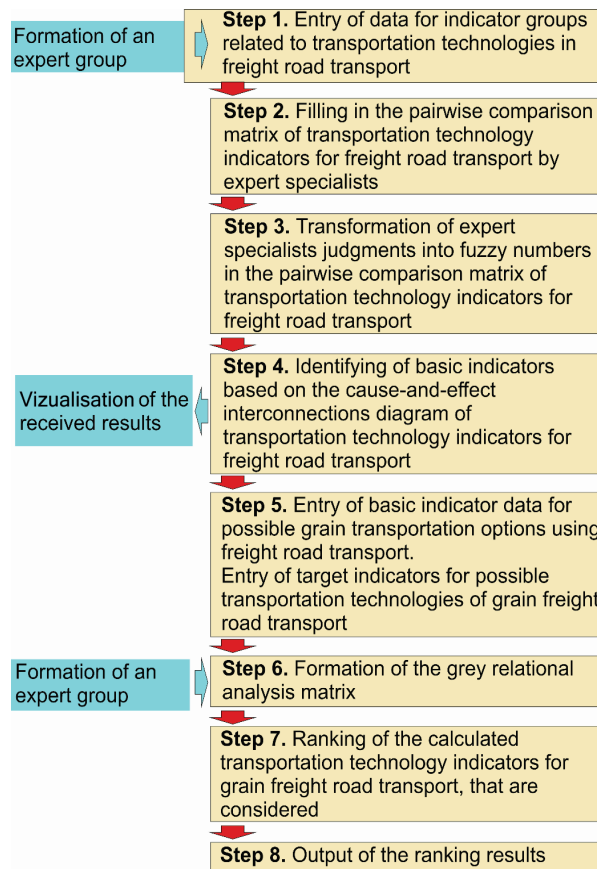


Figure 2. Algorithm for determining the best transport technology for cargo transportation

Source: developed by the authors

Step 1. In module 1, experts entered data on all indicators of transport technology for grain transportation: economic; environmental; safety; energy; technical; ergonomic, transport, etc. (Fig. 3).

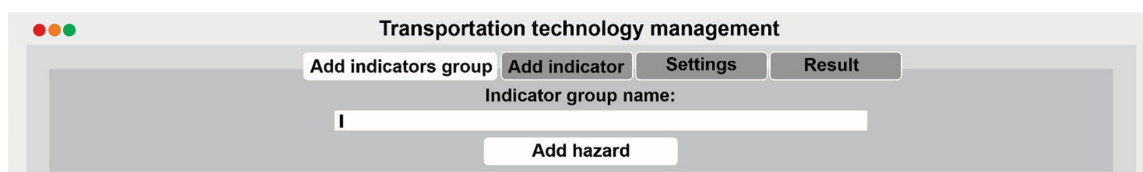


Figure 3. Window for entering transport technology indicators

Source: developed by the authors

Step 2. Module 2 contains expert judgments on the mutual influence of selected indicators in linguistic

terms (Fig. 4), which are then transferred to block 1 of module 4.

Figure 4. A window with a pairwise comparison matrix developed by experts comparing the relationship between indicators

Source: developed by the authors

Step 3. In block 1 of module 4, the experts' judgments were transformed into fuzzy numbers using a fuzzy scale, which involves the use of triangular fuzzy numbers $\tilde{z}$, which are defined as follows: $\tilde{z} = (l, m, u)$, where l, m and u are real numbers and $l \leq m \leq u$. The membership function $\mu_{\tilde{z}}$ is defined as follows (Tsopa et al., 2024):

$$\mu_{\tilde{z}}(x) = \begin{cases} \frac{x-l}{m-l} & \text{if } l \leq x \leq m \\ \frac{u-x}{u-m} & \text{if } m \leq x \leq u \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

The obtained fuzzy numbers provided the opportunity to reduce the uncertainty and subjectivity of expert assessments. This allowed to increase the accuracy and reliability of the model in the process of choosing the best transport technology. The judgments were expressed using a rating scale from 1 to 9, which was previously entered in module 2. 1 point characterises the worst performance, and 9 points – with the best. The collected expert judgments were processed in block 2 with equal weight for all experts and used to create the corresponding matrix of pairwise comparisons.

$$\tilde{z}^k = \begin{bmatrix} 0 & \tilde{z}_{12}^{(k)} & \dots & \tilde{z}_{1n}^{(k)} \\ \tilde{z}_{21}^{(k)} & 0 & \dots & \tilde{z}_{2n}^{(k)} \\ \dots & \dots & \dots & \dots \\ \tilde{z}_{n1}^{(k)} & \dots & \dots & 0 \end{bmatrix}, \quad (2)$$

where $\mu_z = 1, 2, 3, \dots, p$; $\tilde{z}_{ij}^{(k)} = (l_{ij}^{(k)}, m_{ij}^{(k)}, u_{ij}^{(k)})$. Without loss of generality $\tilde{z}_u^{(k)} = (i = 1, 2, \dots, n)$ will be considered as a triangular fuzzy number $\tilde{z} = (0, 0, 0)$, when necessary. Next, the average matrix was calculated from the set of matrices $\tilde{z}_1, \tilde{z}_2, \dots, \tilde{z}_p$ from each involved expert. After its normalisation, a general fuzzy matrix $\tilde{z}_k$ was obtained, which was used to identify and analyse the cause-and-effect relationships between indicators. After constructing the normalised fuzzy matrix $\tilde{z}_k$, an analysis of direct relationships was performed, based on the assumption that:

$$r_k = \max_{i=1}^n (\sum_{j=1}^n u_{ij}^{(k)}). \quad (3)$$

To transform the criteria scale into a scale of comparable values, a linear transformation was used, and normalised fuzzy matrix of direct relationships obtained as a result of expert evaluation:

$$\tilde{x}^k = \begin{bmatrix} \tilde{x}_{11}^{(k)} & \tilde{x}_{12}^{(k)} & \dots & \tilde{x}_{1n}^{(k)} \\ \tilde{x}_{21}^{(k)} & \tilde{x}_{22}^{(k)} & \dots & \tilde{x}_{2n}^{(k)} \\ \dots & \dots & \dots & \dots \\ \tilde{x}_{n1}^{(k)} & \tilde{x}_{n2}^{(k)} & \dots & \tilde{x}_{nn}^{(k)} \end{bmatrix}, \quad (4)$$

where $k = 1, 2, 3, \dots, p$:

$$\tilde{x}_{ij}^{(k)} = \frac{\tilde{z}_{ij}^{(k)}}{r^k} = \left(\frac{l_{ij}^{(k)}}{r^k}, \frac{m_{ij}^{(k)}}{r^k}, \frac{u_{ij}^{(k)}}{r^k} \right). \quad (5)$$

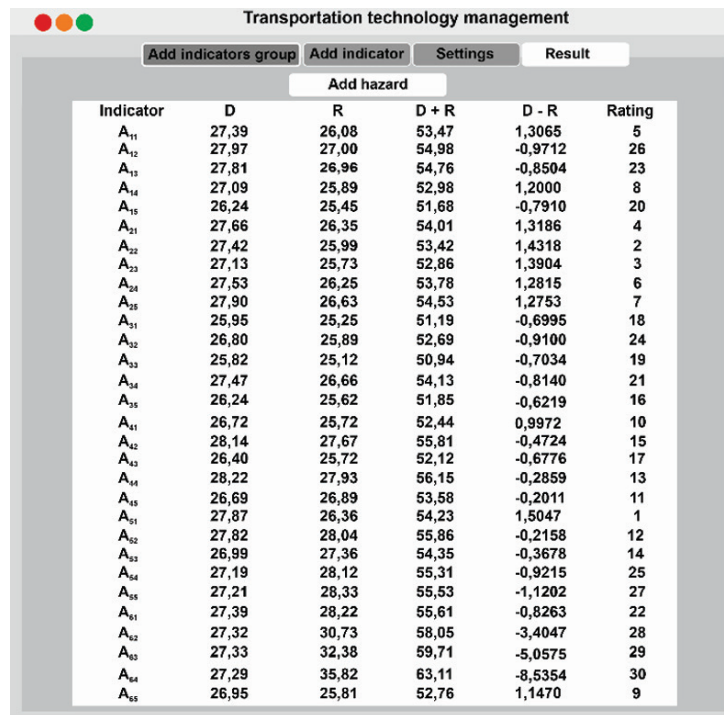
Similarly to the usual fuzzy Dematel method, it was assumed that there is at least one value i that satisfies the condition $\sum_{j=1}^n u_{ij}^k < \sum_{j=1}^n r_j^k$. In this case, the average value of all experts $\tilde{X}$ judgments was calculated as:

$$\tilde{X} = \frac{\tilde{x}^1 + \tilde{x}^2 + \dots + \tilde{x}^p}{p}, \quad (6)$$

$$\tilde{X} = \begin{bmatrix} \tilde{X}_{11} & \tilde{X}_{12} & \dots & \tilde{X}_{1n} \\ \tilde{X}_{21} & \tilde{X}_{22} & \dots & \tilde{X}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{X}_{n1} & \tilde{X}_{n2} & \dots & \tilde{X}_{nn} \end{bmatrix}, \quad (7)$$

$$\text{where } \tilde{X}_{ij} = \frac{\sum_{k=1}^p \tilde{x}_{ij}^{(k)}}{p}.$$

Step 4. In block 2 of module 4, a cause-and-effect diagram was created, based on which the ranking of indicators is automatically provided according to the priority rule by the cumulative percentage – 80% of the total weight of all indicators (Fig. 5). The indicators with the highest rating, which were used in further calculations, were determined as basic. The sum of the rows and columns of the fuzzy general dependency matrix was denoted, respectively, by the vectors D_i and R_i . The data contained in these vectors are functional for creating a cause-and-effect diagram, since its horizontal axis, denoted as $(D_i + R_i)$, determines the indicators influence, while its vertical axis, denoted as $(D_i - R_i)$, indicates the mutual influence degree between the indicators.



Indicator	D	R	D + R	D - R	Rating
A ₁₁	27,39	26,08	53,47	1,3065	5
A ₁₂	27,97	27,00	54,98	-0,9712	26
A ₁₃	27,81	26,96	54,76	-0,8504	23
A ₁₄	27,09	25,89	52,98	1,2000	8
A ₁₅	26,24	25,45	51,68	-0,7910	20
A ₂₁	27,66	26,35	54,01	1,3186	4
A ₂₂	27,42	25,99	53,42	1,4318	2
A ₂₃	27,13	25,73	52,86	1,3904	3
A ₂₄	27,53	26,25	53,78	1,2815	6
A ₂₅	27,90	26,63	54,53	1,2753	7
A ₃₁	25,95	25,25	51,19	-0,6995	18
A ₃₂	26,80	25,89	52,69	-0,9100	24
A ₃₃	25,82	25,12	50,94	-0,7034	19
A ₃₄	27,47	26,66	54,13	-0,8140	21
A ₃₅	26,24	25,62	51,85	-0,6219	16
A ₄₁	26,72	25,72	52,44	0,9972	10
A ₄₂	28,14	27,67	55,81	-0,4724	15
A ₄₃	26,40	25,72	52,12	-0,6776	17
A ₄₄	28,22	27,93	56,15	-0,2859	13
A ₄₅	26,69	26,89	53,58	-0,2011	11
A ₅₁	27,87	26,36	54,23	1,5047	1
A ₅₂	27,82	28,04	55,86	-0,2158	12
A ₅₃	26,99	27,36	54,35	-0,3678	14
A ₅₄	27,19	28,12	55,31	-0,9215	25
A ₅₅	27,21	28,33	55,53	-1,1202	27
A ₆₁	27,39	28,22	55,61	-0,8263	22
A ₆₂	27,32	30,73	58,05	-3,4047	28
A ₆₃	27,33	32,38	59,71	-5,0575	29
A ₆₄	27,29	35,82	63,11	-8,5354	30
A ₆₅	26,95	25,81	52,76	1,1470	9

Figure 5. Window with the result of ranking basic indicators by priority indicator

Source: developed by the authors

Step 5. In module 1, experts entered the values of basic indicators for each transportation technology (in the form of matrix), as well as data on target (reference) indicators for choosing the best solution from the set of alternatives, which are displayed as a series $K^* = [k_1^* \ k_2^* \ \dots \ k_n^*]$. Additionally, experts determined and entered in module 1 the weight coefficients of basic indicators, according to which a matrix was designed in the form $Wk = [w_{k1}, w_{k2}, \dots, w_{kn}]$.

Step 6. In block 3 of module 4, a matrix was designed to determine the relationship between the basic and target indicators of the transportation technology (Lu et al., 2023):

$$K = \begin{bmatrix} k_1^* & k_2^* & \dots & k_n^* \\ A_{11} & A_{12} & \dots & A_{1n} \\ \vdots & \vdots & \ddots & \vdots \\ A_{m1} & A_{m2} & \dots & A_{mn} \end{bmatrix}, \quad (8)$$

where A_{ij} is the value of the i indicator of the k -group of indicators of the j solution; series $K = [k_1 \ k_2 \ \dots \ k_n]$ – is a series of target (reference) values.

The indicators A_{ij} of the matrix K of all m sets of solutions and the values of the 1st group, 2nd group, ..., k -th – group indicators for one dimension are reduced to relative units by dividing into target indicators $k_1, k_2, \dots, k_n$ by the corresponding indicators A_{mi} :

$$\xi_{1i} = A_{1i}/k_i. \quad (9)$$

The target (reference) set of indicators was transferred to the series $K = [k_1, k_2, \dots, k_n]$. Then, using the set of indices K of the reference sequence (determined by the achievable goal) and the matrix A of the compared sequence, the gray ratio coefficient of the j solution for the i group of indicators was obtained by the formula:

$$\xi_{ij} = \frac{\min_{\substack{1 \leq i \leq m \\ 1 \leq j \leq n}} |k_j - A_{ij}| + \rho \max_{\substack{1 \leq i \leq m \\ 1 \leq j \leq n}} |k_j - A_{ij}|}{|k_j - A_{ij}| + \rho \max_{\substack{1 \leq i \leq m \\ 1 \leq j \leq n}} |k_j - A_{ij}|}, \quad (10)$$

$$E = \begin{bmatrix} \xi_{11} & \xi_{12} & \cdots & \xi_{1n} \\ \xi_{21} & \xi_{22} & \cdots & \xi_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \xi_{m1} & \xi_{m2} & \cdots & \xi_{mn} \end{bmatrix}. \quad (11)$$

Step 7. In block 4 of module 4, the achievement index of basic indicators relative to target (reference) indicators of transportation technologies was calculated for each alternative solution for choosing a transportation technology using the formula:

$$R = E \times W = \begin{bmatrix} \xi_{11} & \xi_{12} & \cdots & \xi_{1n} \\ \xi_{21} & \xi_{22} & \cdots & \xi_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \xi_{m1} & \xi_{m2} & \cdots & \xi_{mn} \end{bmatrix} \times \begin{bmatrix} w1 \\ w2 \\ \vdots \\ wl \end{bmatrix} = \begin{bmatrix} r1 \\ r2 \\ \vdots \\ rm \end{bmatrix}. \quad (12)$$

Based on the obtained results of the gray relation matrix (R) an analysis and ranking of transport technologies was carried out. This allowed us to determine the best technology for grain transportation.

Step 8. The results of ranking the set of alternative solutions according to the target (reference) indicators were transferred to module 2 and visualised through module 3 (Fig. 6).

Type of transportation technology	Index of achievement of essential indicators relative to target (benchmark) indicators of transportation technology	Percentage of evaluated compliance with transportation requirements	Transportation technology rating
M1	0,63	19,8	4
M2	0,97	30,6	1
M3	0,64	20,2	3
M4	0,93	29,4	2
Total	3,17	100	

Figure 6. Window with the result of ranking basic indicators by priority indicator

Source: developed by the authors

To select a transport technology for cargo transportation, 5 experts with different experience in organisations transporting agricultural products were selected. The requirements for them are given in Table 1.

When working with the experts, the ethical standards specified in the Guidance note of the European Commission on ethics and data protection (2021) were observed.

Table 1. Requirements for experts involved in the determination

Information	Quantity
Number of experts	Not less than 5
Work experience in positions	from 10 to 14 years
Experts education	higher in the specialty
Work experience	more than 10 years
Auditor's certificate in quality and safety management systems of companies	Yes
Advanced training in risk assessment according to requirements*	Yes

Source: developed by the authors

RESULTS AND DISCUSSION

An example of grain transportation by trucks using four different technologies was considered. Table 2 provides a brief description of the considered transport technologies for grain truck transportation, among which it is

necessary to choose the one that will meet the design (target) indicators (Basnak *et al.*, 2020; Touratier-Muller & Jaussaud, 2021). The justification of the transport technology is based on the assumption that grain can be conditionally transported by different types of trucks.

Table 2. Brief description of possible alternative transport technologies (RFT) or grain truck transportation

No.	Transport technology of road freight transport (RFT)		Brief description of transport technology for grain transport
	Name	Designation	
1.	Tarped road train	M ₁	Tilted freight road train M1 Freight road train consisting of: seat tractor + tarped semi-trailer. Grain is transported by container loading using "big bags". Loading of cargo into the body of the freight road train is carried out using a forklift.

Continued Table 2.

No.	Transport technology of road freight transport (RFT) Name	Designation	Brief description of transport technology for grain transport
2.	Freight road train with a dump semi-trailer	M_2	Freight road train consisting of: seat tractor + dump semi-trailer with rear unloading. Grain is transported in bulk. Loading of cargo into the body of the freight road train is carried out using elevator equipment of self purging.
3.	Freight road train consisting of: dump truck + dump trailer	M_3	Freight road train consisting of: dump truck + dump trailer with side unloading. Grain is transported in bulk. Cargo is loaded into the body of the freight road train using elevator equipment, of self-pouring.
4.	Specialised container for transporting grain, which is transported by a freight road train consisting of: seat tractor + semi-trailer for transporting containers	M_4	Freight road train consisting of: seat tractor + semi-trailer for transporting containers. Grain is transported by container loading using a container. Cargo is loaded into the container using elevator equipment of self-pouring.

Source: developed by the authors

According to the above algorithm, in the first step, indicators groups names and the indicators of freight road transport technology (Table 3) with the corresponding designations were entered into module 1 of software complex. Then, in module 2, a window appeared in which the experts conducted a pairwise comparison of all previously entered indicators of grain transportation transport technology,

based on their influence on each other. After processing the pairwise comparison matrix in module 2, the data were transferred to block 1 of module 4. A normalised fuzzy matrix of direct relationships was constructed in it. Each fuzzy matrix of direct relationships $\tilde{x}^k$ was calculated using fuzzy triangular numbers $\tilde{z}_{ij}^k$ from the matrix $\tilde{z}^k$ based on relations (2) and (4).

Table 3. Indicators catalog of transport technology for grain transportation by road transport

No.	Designation	Group of indicators	Indicator designation	Indicator (factor) name
1.	A_1	Transport factor	A_{11}	Transportation distance, km
			A_{12}	Transport work, tkm
			A_{13}	Transport productivity, t/km
			A_{14}	Cargo preservation during transportation, points (max – 10 points)
			A_{15}	Transport operations performing time, hours
2.	A_2	Operational factor	A_{21}	Cargo volume, tons (vehicle carrying capacity)
			A_{22}	Cargo transportation speed, km/h
			A_{23}	Diesel fuel consumption per 100 km, l/100 km
			A_{24}	Transport process energy intensity, l/km (route length).
			A_{25}	Time spent on transport operations
3.	A_3	Organisational factor	A_{31}	Qualified personnel conducting medical inspection
			A_{32}	Quick registration of accompanying transport documentation
			A_{33}	Efficient process of freight road transportation
			A_{34}	Qualified drivers participating in freight road transportation of grain
			A_{35}	Qualified personnel conducting medical inspection
4.	A_4	Social factor	A_{41}	Driver satisfaction with working conditions at the transport enterprise
			A_{42}	Driver's ability to undergo advanced training (skills)
			A_{43}	Additional leave for the complexity of performing professional duties
			A_{44}	Additional financial payments for the complexity of performing professional duties
			A_{45}	Driver satisfaction with the salary received at the enterprise
5.	A_5	Economic factor	A_{51}	Freight transportation tariff, UAH / ton
			A_{52}	Total cost of all transport operations, UAH
			A_{53}	Cost of transportation, UAH/km
			A_{54}	Profitability, %
			A_{55}	Profit of a motor transport company from transport work, UAH
6.	A_6	Factors related to cargo	A_{61}	Cargo volume, tons
			A_{62}	Productivity of the loading and unloading mechanism, t/h
			A_{63}	Vehicle load capacity utilisation factor
			A_{64}	Adaptability of the vehicle to the transportation of the appropriate cargo type, points (max number – 10 points)
			A_{65}	Reliability (safety) of cargo transportation, points (max number – 10 points)

Source: developed by the authors

Then, based on the averaging of normalised matrices calculated from the pairwise comparison matrices, each expert determined the total normalised fuzzy matrix of direct relationships $\tilde{X}$ based on relations (6) and (7). This allowed calculating the total fuzzy matrix of relationships $\tilde{z}_k$. Then, the sum of rows and the sum of columns were calculated, which were transferred to block 2 of module 4. In block 2, the defuzzification process for the vectors of

significance and relative position of indicators took place. The defuzzification transformation is given in Table 4, where the ratings of cause-and-effect relationships of transport technology indicators were formed. The names of the first 10 indicators were determined as basic. Their names were transferred to module 2 and visualised by module 3 (Table 5). Also, their names have been transferred to block 3 of module 4.

Table 4. Rating of transport technology indicators based on their mutual influence

Indicator	D	R	$D+R$	$D-R$	Rating
A_{11}	27.39	26.08	53.47	1.3065	5
A_{12}	27.97	27	54.98	-0.9712	26
A_{13}	27.81	26.96	54.76	-0.8504	23
A_{14}	27.09	25.89	52.98	1.2000	8
A_{15}	26.24	25.45	51.68	-0.7910	20
A_{21}	27.66	26.35	54.01	1.3186	4
A_{22}	27.42	25.99	53.42	1.4318	2
A_{23}	27.13	25.73	52.86	1.3904	3
A_{24}	27.53	26.25	53.78	1.2815	6
A_{25}	27.9	26.63	54.53	1.2753	7
A_{31}	25.95	25.25	51.19	-0.6995	18
A_{32}	26.8	25.89	52.69	-0.9100	24
A_{33}	25.82	25.12	50.94	-0.7034	19
A_{34}	27.47	26.66	54.13	-0.8140	21
A_{35}	26.24	25.62	51.85	-0.6219	16
A_{41}	26.72	25.72	52.44	0.9972	10
A_{42}	28.14	27.67	55.81	-0.4724	15
A_{43}	26.4	25.72	52.12	-0.6776	17
A_{44}	28.22	27.93	56.15	-0.2859	13
A_{45}	26.69	26.89	53.58	-0.2011	11
A_{51}	27.87	26.36	54.23	1.5047	1
A_{52}	27.82	28.04	55.86	-0.2158	12
A_{53}	26.99	27.36	54.35	-0.3678	14
A_{54}	27.19	28.12	55.31	-0.9215	25
A_{55}	27.21	28.33	55.53	-1.1202	27
A_{61}	27.39	28.22	55.61	-0.8263	22
A_{62}	27.32	30.73	58.05	-3.4047	28
A_{63}	27.33	32.38	59.71	-5.0575	29
A_{64}	27.29	35.82	63.11	-8.5354	30
A_{65}	26.95	25.81	52.76	1.1470	9

Note: D – is the sum of general fuzzy matrix rows; R is the sum of general fuzzy matrix columns; $(D+R)$ – determines the influence of the indicator on the transportation process; $(D-R)$ indicates the degree of mutual influence between the indicators

Source: developed by the authors

Table 5. Basic indicators

Rating	Indicators
1	A_{51} Rating for cargo transportation, UAH/ton
2	A_{22} Cargo transportation speed, km/h
3	A_{23} Diesel fuel consumption per 100 km, l/100 km

Continued Table 5.

Rating	Indicators
4	A ₂₁ Cargo volume, tons
5	A ₁₁ Transportation distance, km
6	A ₂₄ Energy intensity of the transport process, l/km (route length)
7	A ₂₅ Time spent on transport operations
8	A ₁₄ Cargo safety during transportation, points (max – 10 points)
9	A ₆₅ Reliability (safety) of cargo transportation, points
10	A ₄₁ Driver satisfaction with working conditions at a motor transport enterprise

Source: developed by the authors

The analysis of the results obtained from the determination of transport technologies basic indicators showed that the greatest impact is characteristic of economic attractiveness indicators of freight road transportation of the corresponding type of cargo (rating for grain transportation, fuel consumption, energy intensity of the transport process), operational properties of the vehicle (speed and volume of cargo), and also, several indicators related to safety and the human factor (inspector reliability, satisfaction with working conditions) were highlighted. The determination of the basic indicators allows

to proceed to Step 5. The experts entered the values of the basic indicators for each proposed grain transportation technology program (Table 6). Target (reference) basic indicators values related to the motor transport enterprise and will allow to achieve the stated goals were also determined and entered into module 1 (Table 7). Next, data on weighting factors from the specified baseline indicators were generated and entered, which allow obtaining vehicle gray relational coefficients with the specified actual and target (reference) values of baseline indicators for each of the specified technologies.

Table 6. Results of determining indicators by different transport technologies for grain transportation

J-indicator designation	Name of indicators for transport technology	Value of indicators for each transportation technology			
		M ₁	M ₂	M ₃	M ₄
	Indicator designation	A _{1i}	A _{2i}	A _{3i}	A _{4i}
1	Cargo transportation rating, UAH / t	2032	1017	1626	1220
2	Cargo transportation speed, km/h	70	90	60	90
3	Diesel fuel consumption per 100 km, l/100 km	40	35	45	35
4	Cargo volume, tons	20	20	20	20
5	Transportation distance, km	455	455	455	455
6	Energy intensity of the transport process, l/km (route length).	0.0879	0.0769	0.0989	0.0769
7	Time spent on loading and unloading operations, hours	0.9	0.5	0.95	0.67
8	Cargo safety during transportation, points (max – 10 points)	10	7	6	10
8	Carrier reliability, points	9	7	7	9
10	Driver satisfaction with working conditions at a motor transport enterprise, points	9	8	9	8

Source: developed by the authors

Table 7. Target (reference) transport process indicators, which are formed from the set goals

Cargo transportation rating, UAH / t k ₁	Cargo transportation speed, km/h k ₂	Diesel fuel consumption per 100 km l/100 km, k ₃	Cargo volume, tons, k ₄	Transportation distance, km k ₅	Energy intensity of the transport process, l/km (route length), k ₆	Time spent on conducting NRR, h, k ₇	Cargo preservation during transportation, points (max – 10 points), k ₈	Carrier reliability, points k ₉	Driver satisfaction with working conditions at motor transport enterprise, points k ₁₀
1017	90	35	20	455	0.0769	0.5	10	9	9

Source: developed by the authors

The determination of weight coefficients was carried out by experts, using a scale from 0 to 1, where 0 indicates no effect on cargo delivery time and 1 indicates

significant effect. The results of calculating weight coefficients for the above transport technologies are given in Table 8.

Table 8. Results of calculating weight coefficients by basic indicators

Type of transport technology	Cargo transportation rating, UAH/t ξ_{11}	Cargo transportation speed, km/h ξ_{12}	Diesel fuel consumption per 100 km l/100 km, ξ_{13}	Cargo volume, tons, ξ_{14}	Transportation distance, km ξ_{15}	Energy intensity of the transport process, l/km (route length), ξ_{16}	Time spent on conducting NRR, h, ξ_{17}	Cargo preservation during transportation, points (max – 10 points), ξ_{18}	Carrier reliability, points ξ_{19}	Driver satisfaction with working conditions at motor transport enterprise, points ξ_{110}
M1	0.002	0.778	0.857	1.000	1.000	0.857	0.200	1.000	1.000	1.000
M2	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.700	0.778	0.889
M3	0.401	0.667	0.714	1.000	1.000	0.714	0.100	0.600	0.778	1.000
M4	0.800	1.000	1.000	1.000	1.000	1.000	0.660	1.000	1.000	0.889
Average value W	0.250	0.200	0.200	0.050	0.050	0.050	0.050	0.050	0.050	0.050

Source: developed by the authors

At Step 6 in block 3 of module 4, a general matrix is formed for calculating the gray ratio coefficients of the basic indicators by transport technologies for grain transportation according to formulas (8)-(11).

$$K = \begin{bmatrix} 1017 & 90 & 35 & 20 & 455 & 0.0769 & 0.5 & 10 & 9 & 9 \\ 2032 & 70 & 40 & 20 & 455 & 0.0879 & 0.9 & 10 & 9 & 9 \\ 1017 & 90 & 35 & 20 & 455 & 0.0769 & 0.5 & 7 & 7 & 8 \\ 1626 & 60 & 45 & 20 & 455 & 0.0989 & 0.95 & 6 & 7 & 9 \\ 1220 & 90 & 35 & 20 & 455 & 0.0769 & 0.67 & 10 & 9 & 8 \end{bmatrix}$$

Further, in block 4 of module 4, the calculation was carried out using formula 11 of achievement index of basic indicators relative to target (reference) indicators of transportation technologies.

$$R = E \times W = \begin{bmatrix} 0.002 & 0.778 & 0.857 & 1.000 & 1.000 & 0.857 & 0.778 & 1.000 & 1.000 & 1.000 \\ 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 0.889 & 0.700 & 0.778 & 0.889 \\ 0.401 & 0.667 & 0.714 & 1.000 & 1.000 & 0.714 & 0.778 & 0.6 & 0.778 & 1.000 \\ 0.800 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 1.000 & 0.889 \end{bmatrix} \times \begin{bmatrix} 0.25 \\ 0.2 \\ 0.2 \\ 0.05 \\ 0.05 \\ 0.05 \\ 0.05 \\ 0.05 \\ 0.05 \\ 0.05 \end{bmatrix} = \begin{bmatrix} 0.63 \\ 0.97 \\ 0.64 \\ 0.93 \end{bmatrix}$$

Based on the results of the calculations, the above transport technologies for grain transportation were ranked (Table 9).

According to the calculations results, it can be concluded that the best option for the given target indicators will be the transport technology for grain transportation – M₂: a freight road train with a dump semi-trailer (the value of the calculated index value is 0.97). The second place is taken by the transport technology for grain transportation – M₄: a specialised container for transporting grain, which is transported by a freight road train consisting of: seat

tractor unit + a semi-trailer for transporting containers (the value of the calculated index value is 0.93). The third place is taken by the transport technology for grain transportation – M₃: a freight road train consisting of: a dump truck + a dump trailer (the value of the calculated index value is 0.64). The fourth place is taken by the transport technology for grain transportation – M₁: a tarped freight road train (container transportation of grain in “big-bag” bags) (the value of the calculated index value is 0.63). Figure 7 shows a ranking diagram of the transport technologies for grain transportation that were considered.

Table 9. Results of determining the best grain transportation technology

Type of transport technology	Achievement index of basic indicators relative to target (reference) indicators of transportation technologies	Percentage of the estimated level of compliance with transportation requirements, %	Rating of transport technologies
M1	0.63	19.8	4
M2	0.97	30.6	1
M3	0.64	20.2	3
M4	0.93	29.4	2
Total:	3.17	100.0	

Source: developed by the authors

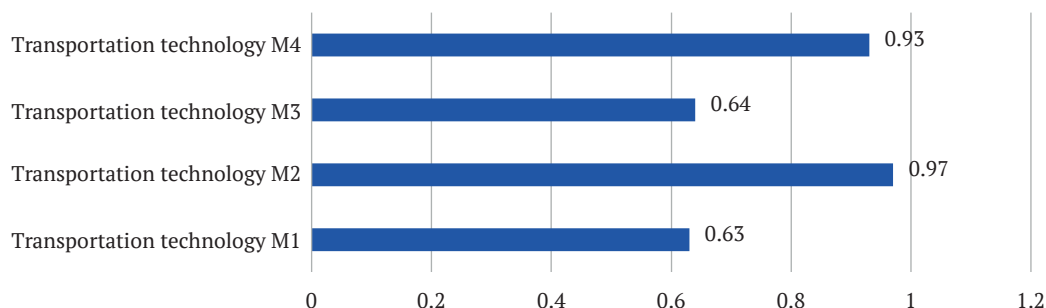


Figure 7. Rating diagram of grain trucking transport technologies

Source: developed by the authors

A software package has been developed for making management decisions regarding the selection of the optimal cargo transportation technology among alternative options. The package consists of four modules: information input, memory, data calculation and output, as well as four blocks: formation of a total matrix of indicator relationships, determination of basic indicators, formation of a gray analysis matrix and selection of the best solution.

The difference of this approach from known methods, in particular the study by K. Čižiūnienė (2022), which was aimed at solving general issues of organising cargo transportation, lies in the combination of two methods: fuzzy DEMATEL and GRA. Such combined use allows to determine the basic indicators characterising the transport technology and, on their basis, selecting the optimal option. The proposed approach ensures the adoption of effective management decisions by comparing the compliance of basic indicators of transport technology with target indicators set in the project of freight road transportation. This corresponds to the priorities of transport industry development and contributes to the introduction of modern information technologies for organising transportation process (Shatilo *et al.*, 2023; Muzylyov *et al.*, 2024; Khomenko *et al.*, 2024).

Analysis of the obtained results shows that the proposed software package allows optimising the process of cargo transportation, reducing vehicle downtime, transportation costs and taking into account the shortage of qualified drivers. Similar aspects were considered in the work of M. Kramchaninova *et al.* (2021), where the main emphasis is made on assessing the problems and prospects for the development of railway freight transportation in Ukraine. The authors note that the efficiency of transport logistics largely depends on innovative approaches to transportation management, which confirms the feasibility of using the developed package to select the optimal transportation technology in existing conditions. However, unlike the results of the study by M. Kramchaninova *et al.* (2021), the proposed model focuses on assessing alternative transportation options taking into account the individual requirements of the customer, which provides greater flexibility in management decisions. An important aspect of the study is the possibility of determining an integral indicator of transport technology efficiency, based on multi-criteria

analysis. Similar approaches were studied in the work of H.I. Nesterenko *et al.* (2023), which analysed the integration of the transport system of Ukraine into the European transport network. The authors note that for successful entry into the European transport space, it is necessary to implement digital technologies for assessing the efficiency of routes and transportation, which confirms the relevance of using the proposed software package. At the same time, if in the study of H.I. Nesterenko *et al.* (2023) the main emphasis is made on macroeconomic aspects of transport system integration, the results obtained are focused on microeconomic level, offering tools for improving the efficiency of individual carriers. The use of gray relational analysis to determine a complex indicator of transport solutions efficiency, which is a key element of the proposed model, deserves special attention. The study of D. Shmatko *et al.* (2021) also considers the possibilities of optimising rolling stock selection and inventory management, using mathematical modelling to improve logistics decisions. The results obtained are consistent with the conclusions of D. Shmatko *et al.* (2021), as they confirm the effectiveness of mathematical approaches in logistics planning. At the same time, the proposed approach is more flexible, as it allows evaluating different transportation options according to a number of independent criteria, taking into account the specific features of the transport process.

The analysis of the obtained results shows that the proposed software package can be an effective tool not only for choosing the optimal transport technology, but also for predicting fuel consumption during road transportation. Optimisation of fuel consumption is an important task for reducing the cost of logistics processes, which is consistent with the conclusions of T. Škrinjarčić & B. Šego (2019). Using fuzzy Dematel to determine the relationships between various factors allows to improve the accuracy of route assessment, which is also noted in the work of T. Škrinjarčić (2020).

Unlike traditional methods of vehicle fleet selection, such as queuing theory (Zakeri *et al.*, 2022), object-oriented programming (Fausto *et al.*, 2020) or regression analysis (Onoprienko, 2021), the developed approach offers a multi-criteria analysis that takes into account complex factors and allows finding the most effective solutions according to specific conditions. Additionally, the results

correlate with the findings of M. Scorrano *et al.* (2020) and N. Touratier-Muller & J. Jaussaud (2021) as to the impact of transport parameters on overall costs and transportation environmental sustainability.

The obtained results confirm the effectiveness of the proposed software package in selecting the optimal transport technology, which is based on the analysis of ten key indicators, including the speed of cargo delivery and fuel consumption. Similar criteria for assessing the competitiveness of freight transportation were considered in the study by N. Khanna *et al.* (2021), which analysed strategic approaches to the decarbonisation of freight transport. The conclusions obtained in this study are consistent with the results of M. Hu *et al.* (2024), which identified the most effective technology for transporting large-sized cargo. However, in the above works, the main attention was paid to fuel characteristics as the main factor in choosing a transport technology, while in the proposed model this aspect can be taken into account by changing the weight coefficients of the relevant indicators, which allows for more flexible adaptation of the approach to specific conditions.

An important aspect is consumer orientation, since target indicators can be adjusted according to the needs of the customer. A similar approach was considered in the work of C. Cao *et al.* (2021), where an algorithm for selecting a transport technology with the possibility of adjusting weighting coefficients using additional assessment methods was proposed. This is consistent with the concept of flexible logistics process management implemented in this study.

Not only economic feasibility has a significant impact on transport technology choice, but also environmental and social aspects, which are key elements of sustainable regional development (Yan *et al.*, 2024; Pu *et al.*, 2024). Reducing the cost of transportation, environmental load and social losses are important factors that need to be integrated into transport strategies. The obtained results indicate the possibility of further improving the software package by adding risk management modules and expanding the functionality to predict potential threats associated with disruptions to logistics processes.

Thus, the developed software package provides broader opportunities for optimising transport processes, allowing to take into account not only transportation efficiency, but also economic and environmental aspects, which makes it competitive in comparison with other logistics solutions assessing methods. Thus, the conducted study demonstrates the practical effectiveness of the developed methodology in transport technologies selection, confirming its relevance to modern approaches in the field of logistics and sustainable development. The proposed approach provides flexibility in decision-making, allowing to adapt the choice of transport technology to the specific requirements of customers and external conditions. The obtained results indicate using potential of the developed software package to increase the logistics processes efficiency, including reducing costs, optimising resources and increasing the transportation environmental sustainability.

CONCLUSIONS

A software package is proposed for making a management decision to choose the best cargo transportation technology from a set of alternatives, which consists of four modules (information input, memory, calculation and data output) and four blocks located in the calculation module (block 1 for forming a total matrix of indicator relationships, block 2 for determining basic indicators and a block for forming a gray analysis matrix and block 4 for choosing the best solution from a set of alternative solutions) based on the methods: fuzzy Dematel and GRA, which are used to determine basic indicators and based on them, choose the transport technology for grain transportation itself. The software complex implements a seven-Step algorithm: entering groups of indicators, analysing them pairwise, determining basic indicators based on the total matrix of relationships, entering values of basic and reference indicators of grain transportation technologies and weighting factors, constructing gray analysis matrices, determining the index of basic indicators achievement relative to target ones.

As a result, the best transport technology for transporting grain was selected to meet the target (reference) indicators of the motor transport enterprise according to the following indicators: cargo transportation rating; cargo transportation speed; diesel fuel consumption per 100 km; cargo volume; transportation distance; energy intensity of the transport process; time spent on loading and unloading operations; cargo safety during transportation; carrier reliability; driver satisfaction with working conditions. According to the calculations results, the transport technology for transporting grain from a freight truck with a dump semi-trailer best meets the target indicators. The dependence of the basic indicators of the transport technology for transporting cargo and the target indicators of the motor transport enterprise was established, which allows improving the algorithm for making a management decision to choose an effective transportation technology from a set of alternative ones.

Further research will be aimed at developing the possibilities of integrating the software complex with existing transport logistics systems used in logistics terminals. This will allow for automated data exchange, increase the efficiency of route planning, and optimise grain loading and unloading processes.

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CONFLICT OF INTEREST

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Віталій Цопа

Доктор технічних наук, професор
Міжнародний інститут менеджменту
04116, вул. Шулявська, 10/12, м. Київ, Україна
<https://orcid.org/0000-0003-4652-9180>

Тамара Білько

Кандидат біологічних наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0000-0003-3164-3298>

Сергій Чеберячко

Доктор технічних наук, професор
Національний технічний університет «Дніпровська політехніка»
49005, просп. Дмитра Яворницького, 19, м. Дніпро, Україна
Технічний університет «Метінвест Політехніка»
69008, Південне шосе, 80, м. Запоріжжя, Україна
<https://orcid.org/0000-0003-3281-7157>

Олег Дерюгін

Кандидат технічних наук, доцент
Національний технічний університет «Дніпровська політехніка»
49005, просп. Дмитра Яворницького, 19, м. Дніпро, Україна
<https://orcid.org/0000-0002-2456-7664>

Богдан Гримало

Аспірант
Національний технічний університет «Дніпровська політехніка»
49005, просп. Дмитра Яворницького, 19, м. Дніпро, Україна
<https://orcid.org/0009-0003-9523-460X>

**Програмний комплекс з вибору транспортної технології
перевезення зерна вантажним автомобільним транспортом**

Анотація. Метою роботи було розробити програмний комплекс для прийняття управлінського рішення для вибору транспортної технології перевезення зерна автомобільним транспортом із множини альтернатив. Для досягнення поставленої мети використано метод морфологічного аналізу, який заснований на підборі можливих рішень для окремих частин завдання. Запропоновано програмний комплекс для прийняття управлінського рішення із множини альтернатив, який складався з чотирьох модулів та чотирьох блоків. В його основі знаходились два метода: fuzzy Decision Making Trial and Evaluation Laboratory (далі – fuzzy Dematel) і сірого реляційного аналізу (далі – GRA), які використовувалися для визначення базових показників та на їх основі вибір самої транспортної технології перевезення зерна. В програмному комплексі реалізовано алгоритм з восьми кроків: вводу груп показників, їх попарному аналізу, визначення базових показників на основі сумарної матриці зв'язків, вводу значень базових та еталонних показників транспортних технологій перевезення зерна та вагових коефіцієнтів, побудови матриць сірого аналізу, визначення індексу досягнення базових показників відносно цільових. В результаті обрано кращу транспортну технологію вантажних автомобільних перевезень зерна до цільових (еталонних) показників автотранспортного підприємства за наступними показниками: тариф на транспортування вантажу; швидкість транспортування вантажу; витрата дизельного палива на 100 км; обсяг вантажу; відстань транспортування; енергоємність транспортного процесу; час, який витрачений на проведення навантажувально-розвантажувальних робіт; збереження вантажу при транспортуванні; надійність перевізника; задоволеність водієм умовами праці. За результатами проведених розрахунків зазначено, що найкраще задовольняє цільовим показникам транспортна технологія перевезення зерна – вантажним автопотягом з самоскидним напівприцепом. Встановлено залежності базових показників транспортної технології перевезення вантажу і цільовими автотранспортного підприємства, що дозволяє вдосконалити алгоритм прийняття управлінського рішення з вибору ефективної транспортної технології перевезення із сукупності альтернативних. Запропонований процес вибору кращого рішення із сукупності альтернативних може використовуватися в організаціях, які здійснюють вибір кращої технології вантажних автомобільних перевезень сипких вантажів – зерна

Ключові слова: транспортна технологія, метод fuzzy Dematel, метод сірого реляційного аналізу, цільові показники, еталонні показники, управлінські рішення

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Valeriy Adamchuk

Doctor of Technical Sciences, Professor, Academician
Institute of Mechanics and Automation of Agro-industrial Production
of the National Academy of Agrarian Sciences of Ukraine
08631, 11/1 Vokzalna Str., Hlevakha village, Kyiv region, Ukraine
<https://orcid.org/0000-0003-0358-7946>

Serhiy Pohorilyy

Doctor of Technical Sciences
Institute of Mechanics and Automation of Agro-industrial Production
of the National Academy of Agrarian Sciences of Ukraine
08631, 11/1 Vokzalna Str., Hlevakha village, Kyiv region, Ukraine
<https://orcid.org/0000-0002-9701-2678>

Viktor Prysyzhnyy

PhD in Technical Sciences
Institute of Mechanics and Automation of Agro-industrial Production
of the National Academy of Agrarian Sciences of Ukraine
08631, 11/1 Vokzalna Str., Hlevakha village, Kyiv region, Ukraine
<https://orcid.org/0000-0001-5096-3241>

Vadym Yaremenko*

PhD in Technical Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0002-3271-6287>

Valerii Mirnyi

Postgraduate Student
Institute of Mechanics and Automation of Agro-industrial Production
of the National Academy of Agrarian Sciences of Ukraine
08631, 11/1 Vokzalna Str., Hlevakha village, Kyiv region, Ukraine
<https://orcid.org/0000-0003-0560-2484>

**Aggregation of a mobile energy vehicle
of the “Autotractor” with a technological module**

Abstract. The relevance of the research was determined by necessity to increase the efficiency of machine and tractor units (MTUs) in both traction-powered and transport-technological operations, while ensuring operational safety. The objective of the research was to experimentally determine the effect of the mass of the technological module (TM) on the axle loads of a mobile energy vehicle (MEV) of the “Autotractor” during aggregation with a rear-mounted three-point hitch. The research addressed the issue of stability and load distribution in MTUs, particularly those with MEVs

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*Corresponding author



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of the “Autotractor” based on high-mobility truck platforms. The MEV-115 “Autotractor”, developed at the Institute of Mechanics and Automation of Agro-Industrial Production of the National Academy of Agrarian Sciences of Ukraine, was introduced. This vehicle featured several innovative design solutions, including a centralised tyre pressure control system, a hydraulic system, a frame-based TM mounting system, and a specially designed rear three-point hitch. The hitch structure enabled aggregation with TMs weighing up to 2 tonnes. Its compact design allowed for hassle-free mounting of the TM onto the vehicle frame without disassembling the hitch. Experimental research using strain gauge scales was carried out to verify theoretical calculations on the distribution of axle loads in the MEV depending on the weight and centre of mass of the TM. Critical TM parameters were established for safe operation: the distance from the TM’s centre of mass to the rear axle (0–4 m) and the TM weight (6.39–18.7 kN). TM configurations ensuring balanced axle loads were also defined, eliminating parasitic power circulation between the axles of the MEV-115 “Autotractor”. The minimum front axle load necessary to maintain steerability during transport operations was determined to be at least 20% of the total MTU weight. The results confirmed the validity of the theoretical models and demonstrated the effectiveness of the approach. The findings may be applied to enhance MEV design and optimise their use in agricultural production

Keywords: experimental research methods; measuring equipment; sensor calibration; tractor; mobile energy vehicle (MEV)

INTRODUCTION

The research into aggregation processes has been essential for ensuring the effective and safe operation of agricultural and industrial machinery. It enabled the optimisation of the interaction between mobile energy vehicles (MEVs) and technological modules (TMs), increasing the efficiency of operations and reducing energy consumption. The research allowed for a comprehensive assessment of critical parameters such as weight, centre of mass coordinates, structural stability, and the load on key MEV components. Determining these characteristics contributed to optimising load distribution, enhancing vehicle stability and reliability, reducing wear of main components, and thereby extending service life, minimising maintenance and repair costs, and improving the overall efficiency of the unit in varied operating conditions. Moreover, analysing the interaction between aggregated components facilitated improved structural designs, increased manoeuvrability, and adaptation of the machinery to different working environments – factors critical to the advancement of modern mobile technologies.

Previous scientific efforts had largely focused on developing tractor stability models, evaluating their static and dynamic properties, and proposing methodological frameworks for assessing stability. However, the stability parameters of MEVs of the “Autotractor” type, particularly during aggregation with TMs, remained insufficiently researched. The stability of motion and load distribution in MEV-based MTUs was of paramount importance. These processes underpinned safe movement during transport, transitions with attached implements, soil compaction concerns, and overall safety. For instance, research by G. Carabin *et al.* (2023) highlighted that over 100 fatal accidents involving tractor rollovers were recorded annually in Italy – posing not only a risk to human life but also causing significant financial losses due to equipment damage and operational downtime.

M. Bietresato & F. Mazzetto (2020) pointed out that international standards for evaluating the stability of

agricultural machinery lacked sufficient detail. These standards typically focused only on the roll-over angle and failed to account for operational factors such as soil type, tyre pressure, and terrain slope. The authors introduced a new test platform capable of more accurately determining the centre of mass and assessing stability in various positions. However, that research did not address dynamic load effects during motion, necessitating further research. Researchers B. Franceschetti *et al.* (2021) emphasised the heightened rollover risk associated with articulated narrow-track tractors. They developed a kinematic model to simulate tractor behaviour virtually, enabling the determination of a minimum transverse stability angle (39.3° at a -35° pitch angle). While these results could assist in optimising tractor design for greater stability, they specifically concerned articulated-frame MEVs and thus required refinement for application to the “Autotractor”-type MEVs.

According to V. Rondelli *et al.* (2013), despite the mandatory use of rollover protective structures (ROPS), tractor instability incidents remained a significant concern. The authors investigated the impact of various factors—soil morphology, climatic conditions, and operator experience – on tractor stability. They utilised a real-time monitoring system to evaluate rollover risks and suggest corrective actions, although the research did not assess the long-term effectiveness of these interventions. G. Prevati *et al.* (2014) explored tractor stability on slopes using mathematical models to determine tipping thresholds. Their analysis included tyre stiffness, asymmetric implement placement, and a comparison between traditional front axles and passive suspensions. While they found that suspension systems could improve stability, their research did not include dynamic parameters such as speed or varying loads, indicating the need for further investigation.

D. Pessina *et al.* (2022) researched the lateral stability limitations of narrow-track agricultural tractors and the influence of design features (wheels, tyre pressure, and accessories) on rollover resistance. Their research covered

tractors of different constructions but did not include dynamic field conditions, calling for extended researches to better predict stability in real-world settings. In contrast, S.P. Pogorilyy *et al.* (2022; 2023) focused on justifying traction performance indicators for MEVs. However, their work considered the design and aggregation parameters of TMs only in general terms, without addressing the physical processes occurring during aggregation.

Taking into account the predominance of research dedicated to conventional tractor-layout MEVs, it became evident that researching the stability of “Autotractor”-type MEVs was crucial for both agricultural professionals and vehicle manufacturers. The aim of this research was to explore the impact of TM mass on axle loads in the “Autotractor” – type MEV in order to reduce operational costs by designing and implementing agricultural units based on this MEV configuration.

MATERIALS AND METHODS

The object of the research was the multifunctional MEV-115 “Autotractor”, developed in 2023 at the Institute of Mechanics and Automation of Agro-Industrial Production of the National Academy of Agrarian Sciences of Ukraine (Pogorilyy *et al.*, 2022; 2023) (Fig. 1). The machine was equipped with a custom-designed three-point hitch. The mass of the MEV-115 “Autotractor” amounted to 3500 kg, with an internal combustion engine rated at 88.3 kW (115 hp), a wheel arrangement of 4x4, and a maximum speed of 90 km/h.



Figure 1. Mobile Energy Vehicle MEV-115 “Autotractor”

Source: compiled by the authors

A key feature of the MEV-115 “Autotractor” was the centralised tyre pressure control system, which allowed for pressure reduction during field operations (0.05–0.07 MPa) and an increase to the recommended value for road transport (0.27 MPa). This system also allowed for dynamic pressure adjustment during technological operations, depending on the weight of the TM. The MEV-115 “Autotractor” was designed as an alternative to tractors of traction class 1.4 (with a drawbar pull of 14 kN), which were primarily used for transport and technological operations whose efficiency was largely influenced by moving distance. Under such conditions, the MEV-115 “Autotractor” was required to aggregate with TMs (machines or implements) designed for class 1.4 tractors.

To examine the operation of the three-point hitch and to research the processes that occurred during aggregation with the TM, experimental research was carried out. The following criteria were established for the performance of the three-point hitch: time required to lift the TM from the lower to upper position, time to lower it, the distribution of loads on the MEV’s axles, and the hydraulic pressure in the MEV’s system during aggregation.

For the experimental researches, 20 kN-capacity strain gauge vehicle scales of the VAPO-15 type were used. These were manufactured by scientific-testing institutes of the former Soviet Union. Prior to conducting the research, the scales were calibrated using certified equipment, in particular the DOSM-3-3 dynamometer (Ukraine). The calibration was performed in 200 kg increments from 0 to 2000 kg. Data registration was carried out using an L-CARD-E14-440 AD/DA converter and LGraph2 software.

Through regression analysis, quantitative dependencies were established that supported engineering decisions regarding the MEV’s design and operation. A force diagram (Fig. 2) representing the MEV-115-based MTU was used to derive the chain between the MEV’s parameters and the aggregated TM mounted on the rear three-point hitch.

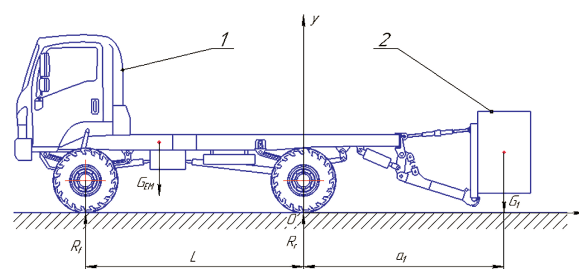


Figure 2. Force diagram of the machine-tractor unit

Note: 1 – MEV; 2 – rear TM; G_{TM} – MEV weight, kN; G_1 – TM weight, kg; R_f , R_r – load on the front and rear MEV axles respectively, kN; L – MEV wheelbase, m; a_1 – distance from the rear axle to the TM’s centre of mass, m

Source: compiled by the authors

Regression analysis was employed to determine the correlation between TM mass and axle loads on the MEV during aggregation with the rear three-point hitch. This analysis enabled the following: assessment of the influence of TM weight on load redistribution between axles; identification of critical loading values affecting the MEV’s stability and steerability; development of a mathematical model to forecast axle loads for different TM masses; and optimisation of aggregation parameters to ensure efficient operation without overloading or adverse effects on the vehicle’s handling.

RESULTS AND DISCUSSION

Based on the theoretical research (Pogorilyy *et al.*, 2023), the dependencies of the loads on the front and rear axles of the MEV on the mass of the technological module (TM) were determined:

$$P_r = 1.9091 \cdot m + 13.806, \quad (1)$$

where P_r – rear axle load, kN; m – cargo mass, kg.

$$P_f = -0.909 \cdot m + 20.194, \quad (2)$$

where P_f – front axle load, kN.

A graphical representation of the obtained results is presented in Figure 3.

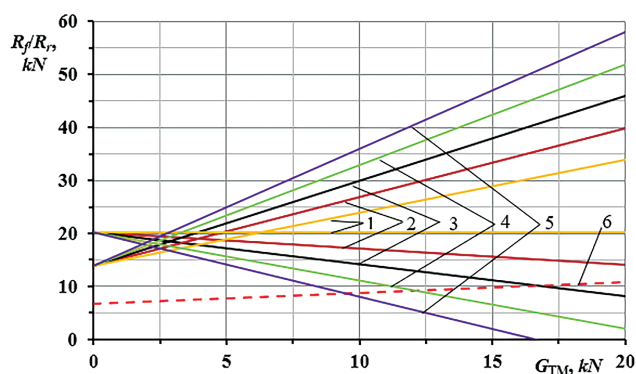


Figure 3. Dependence of axle loads on the mass of the TM

Note: 1, 2, 3, 4, 5 – loads on the front and rear axles according to the change in the coordinate of the center of mass of the TM from the axis of the rear wheels: 0; 1; 2; 3; 4 m; 6 – limit of controllability of the unit

Source: compiled by the authors

According to the results of theoretical calculations, the parameters of the technological module (TM) aggregated via the rear-mounted three-point hitch of the MEV-115 “Autotractor” were determined. Specifically, the distance from the TM’s centre of mass to the centre of the rear axle ranged from 0 to 4 metres, while the TM weight varied from 67 to 9.5 kN. For instance, with a TM weight of 20 kN and a centre of mass located 3 m behind the rear axle, the load on the front axle of the MEV decreased from 20.2 to 2.01 kN, whereas the load on the rear axle increased from 13.8 to 52 kN. Under the condition of equal axle loading, the distance from the TM’s centre of mass to the MEV’s rear axle ranged from 0 to 4 metres, while the TM weight varied from 6.39 to 1.87 kN. The limiting factor for the TM weight was the minimum required load on the front axle of the MEV to ensure adequate steerability of the unit during transport operations, which had to be no less than 20% of the total weight of the machine-tractor unit (line 6 in Fig. 3). In this case, for a TM weight of 12 kN, the minimum required front axle load for the MEV was 9 kN.

To verify the theoretical data obtained, experimental research was conducted. A methodology was developed to carry out experimental investigations aimed at determining the influence of TM parameters on the characteristics of the MEV of the “Autotractor” type (Pogorilyy *et al.*, 2023). In light of the above, it became necessary to perform researches to validate the theoretical data by

experimentally determining the effect of the TM mass on the axle loads of the MEV.

To assess the adequacy of the theoretical results obtained, experimental research was conducted. In accordance with the methodology developed by S.P. Pogorilyy *et al.* (2023), measurements of the loads on both the front and rear axles of the MEV were performed. The axle loads of the MEV were determined using strain gauge scales. Since the MEV combined with the TM was symmetrical in the longitudinal plane, it was sufficient to take readings and record measurements from one side of the MEV (Fig. 4).



Figure 4. Placement of strain gauges on the MEV-115 “Autotractor”

Source: compiled by the authors

The tank and additional ballast were used as the technological module (TM), allowing the TM mass to be varied from 500 kg to 1500 kg (Fig. 5). The experimental researches were conducted in the following sequence: first, the TM was lifted from the supporting surface, during which, at the moment of rest, the TM mass exerted no load on the MEV axles. The TM was then raised to its upper position until the safety valve of the hydraulic system was activated at a pressure of 13.5 MPa, with the internal combustion engine of the MEV-115 “Autotractor” at 3000 rpm. Subsequently, the TM was lowered from the upper position until the load was removed from the rear axle due to the mass of the TM.



Figure 5. General view of MEV-115 with TM during the experiment

Source: compiled by the authors

The strain gauge scales registered the loads that arose during the experiments, and the signal from them was transmitted to an analogue-to-digital converter and

recorded on a personal computer using the LGraph2 software (Fig. 6). The data sampling frequency was 10 kHz. During the 12 experimental trials conducted, the

variable parameter was the TM mass, which ranged from 0 to 1500 kg with an increment of 500 kg. Each measurement was repeated three times.

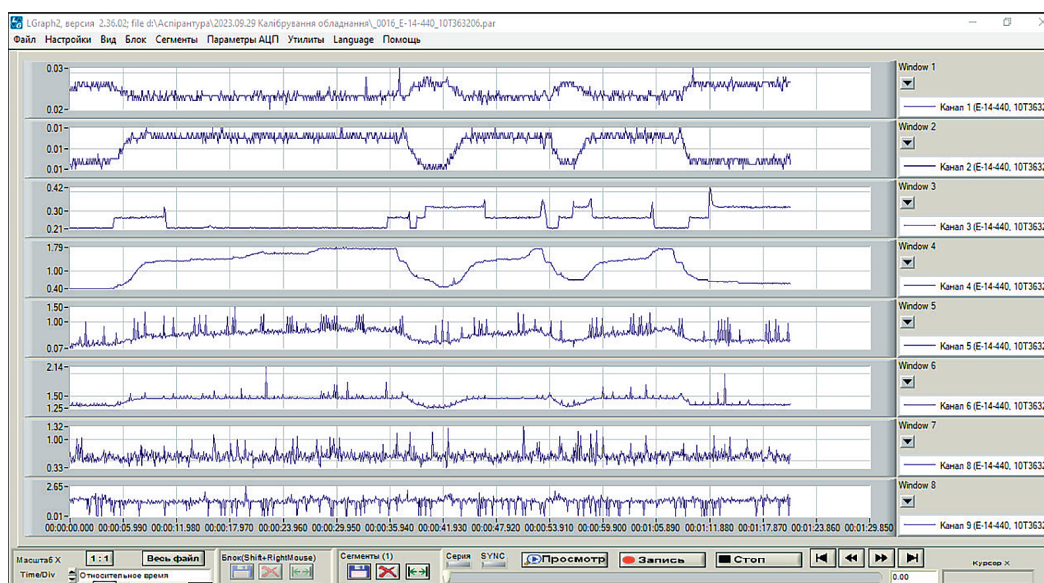


Figure 6. LGraph2 program window during experiment

Source: compiled by the authors

The data obtained were converted from voltage (V) values into load (kN), with each strain gauge scale having its own calibration characteristic determined during the tare procedure. The subsequent processing of the experimental data involved calculating the average value for each trial, the variance, and the standard deviation. All collected data conformed to a normal distribution. Based on the results of the experimental data processing, regression equations were obtained that described the chain between the TM mass and the axle loads of the MEV:

$$P_r = 0.0194 \cdot m + 12.837, \quad (3)$$

where P_r – rear axle load, kN; m – cargo mass, kg.

Dependence of front axle load:

$$P_f = -0.0094 \cdot m + 21.263, \quad (4)$$

where P_f – load on the front axle, kN.

The regression equations had a coefficient of determination (approximation probability) of 0.99. Based on regression equations (3-4), graphical dependencies were constructed to illustrate the changes in front and rear axle loads depending on the variation in the mass of the three-point hitch (Fig. 8). The obtained regression equations (3-4) made it possible to research the influence of the three-point hitch mass on the axle loads of the mobile energy vehicle (MEV), allowing the determination of the required hitch mass to be aggregated with the MEV in order to achieve equal loads on the wheels. Under such conditions, the circulation of “parasitic” power between the axles did

not occur. As shown in Figure 7, when the three-point hitch mass increased from 0 to 1500 kg, the rear axle load rose from 1200 to 4500 kg, while the front axle load decreased from 2100 to 600 kg. This corresponded to the requirements of DSTU 2189-93 (1994), which specified the need to ensure the controllability of the mobile technical aggregate (MTA) on public roads. The calculations confirmed compliance with the requirement $R_f = 0.2 \cdot G_r$ (G_r – was the total weight of the MTA (Pogorilyy et al., 2023; Loveikin et al., 2024).

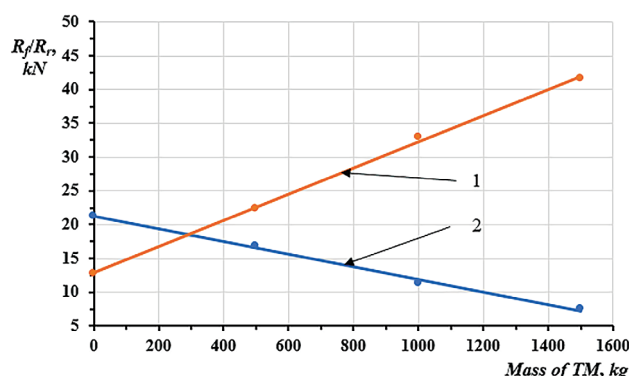


Figure 7. Experimental dependence of axle loads on the mass of the technological module

Note: 1 – rear axle load; 2 – front axle load

Source: compiled by the authors

To verify the adequacy of the theoretical results with respect to the experimental data, a method was used that involved constructing confidence intervals for the experimental data, as proposed by L.V. Viktorova et al. (2017) (Fig. 8).

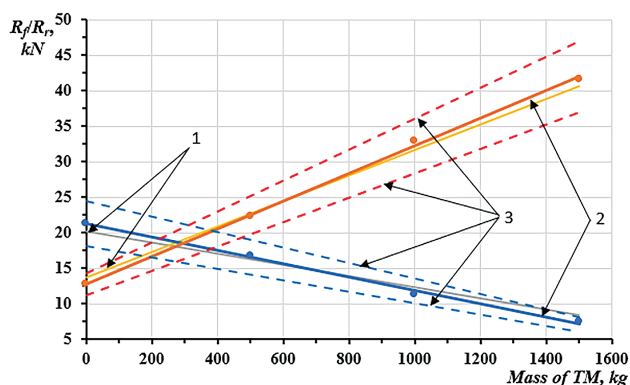


Figure 8. Verification of the adequacy of the experimental research

Note: 1 – theoretical dependence of front and rear axle loads; 2 – experimental dependencies of front and rear axle loads; 3 – confidence intervals

Source: compiled by the authors

The location of the theoretical dependence within the calculated confidence intervals of the experimental data indicated their adequacy with respect to the experimental results. As seen in Figure 9, the nature of both the experimental and theoretical dependencies was similar, and the condition ($R_f = R_r$) was observed under comparable three-point hitch parameters. The theoretical data fell within the confidence intervals, confirming their adequacy with a confidence probability of 95%.

The research results of other authors working in this field demonstrated the following. In the research by H. Yang *et al.* (2020), the issue of tractor rollover on slopes was considered, particularly at an incline angle of approximately 15°. The authors developed a mathematical model of tractor rollover, which accounted for the kinematics of motion, forces acting on the wheels, and the influence of lateral acceleration. The model was tested using the CarSim/Matlab Simulink environment to analyse the tractor's dynamic behaviour. The research also assessed the effectiveness of an active stability control system designed to reduce the risk of rollover on slopes. The main conclusion was that as lateral acceleration increased, the load on the left wheel decreased, and when it reached zero, the tractor lost stability and overturned.

Researchers V. Vantsevich *et al.* (2016) proposed a method for optimising the mobility of a hybrid 4×4 wheeled vehicle by investigating axle loads and power distribution control. A mobility index and Lagrange multiplier were used to determine the optimal power distribution. A control algorithm was developed that adjusted the power split to maintain the optimal trajectory.

The findings reported by I. Ahmadi (2011) showed that tractor stability on slopes depended not only on rollover risk but also, to a large extent, on the risk of lateral slippage. The author proposed a dynamic model of tractor lateral rollover that took into account external positional disturbances, enabling a quantitative assessment of the in-

fluence of ground inclination, travel speed, and machine design features on overall stability. It was established that slippage was a more critical factor in the loss of tractor stability than rollover, particularly under conditions of increased slope angles and when moving at speeds exceeding 5 m/s. Specifically, when the slope angle increased beyond 15°, the risk of lateral slippage rose non-linearly, significantly reducing safety levels. Furthermore, the model accounted for the effects of tyre type, tractor centre of mass, and suspension stiffness, which were essential for evaluating the machine's dynamic performance.

In the work of G. Golub *et al.* (2023), a mathematical model was presented for determining soil reactions and, accordingly, the pressure exerted by tractor drive systems on the soil, depending on the tractor's structural parameters. The model's adequacy was assessed, and an example was provided for calculating the weight distribution across the tractor axles. A. Keller *et al.* (2023) developed an algorithmic framework for the multi-criteria optimisation of the functional properties of mobile power units (MPUs) in agriculture. The key quality criteria identified included: soil pressure, productivity, fuel and energy efficiency, maintenance costs, and overall energy efficiency. The work of E. Sangenis *et al.* (2025) resulted in the development of a software suite for the multi-criteria optimisation of active vehicle safety. The universal MOVI software was used as the optimisation module. In the research by H. Silleli *et al.* (2008), a prototype of an anchoring mechanism was presented, designed to increase the operator's safety zone on narrow-track wheeled agricultural tractors. The researchers developed the device's design, described its working principle, and conducted initial experimental tests. The results demonstrated that the proposed mechanism could effectively reduce the risk of injury to the driver in the event of a rollover, without compromising the tractor's controllability or stability during operation.

The article by B. Franceschetti *et al.* (2014) examined the effectiveness of a mathematical model of tractor rollover dynamics by comparing its results with real-world tests on lateral stability. The authors carried out numerical simulations and experimental testing to verify the model's accuracy under slope-working conditions. The results showed a high level of agreement between the simulations and practical data, confirming the usefulness of such a model for predicting rollover risk and improving safety in agricultural applications.

V. Bulgakov *et al.* (2021; 2024) investigated methods to improve the efficiency of using modular tractor constructions. It was determined that such constructions were limited by increased travel speed due to vertical oscillations caused by ground unevenness. Experiments showed that throttling the hydraulic system of the energy module's rear suspension could reduce the amplitude of vertical oscillations by 15-20%, lower peak frame loads by 10-12%, and decrease fuel consumption by 3-5%. This contributed to improved ride smoothness and increased operational efficiency of the aggregates.

The results of research into the processes occurring in MEVs and MTAs during field movement, operation on slopes, and aggregation with three-point hitches played a significant role and were essential for improving existing MEVs and MTAs and for developing new designs.

CONCLUSIONS

The obtained results of the research on the process of aggregating the three-point hitch (TM) with the mobile energy vehicle (MEV) made it possible to theoretically investigate the aggregation process and justify the parameters for safe performance of technological operations during transport movements of the MTA based on the MEV-115 “Autotraktor”. The theoretically established chain between the parameters of the TM and the MEV during aggregation using the rear three-point hitch allowed the determination of axle loads of the MEV for given TM parameters. In cases of uneven load distribution between the front and rear axles, a difference in tyre deflection occurred, which altered their rolling radii. As the MEV-115 “Autotraktor” was not equipped with an inter-axle differential, it was important to ensure an even load distribution between the axles ($R_f = R_r$). This made it possible to avoid the appearance of parasitic power, reduced fuel consumption, minimised soil compaction, and increased the traction efficiency coefficient of the MEV.

Based on these chains, a graph showing the dependence of front and rear axle loads on TM weight was constructed. Theoretical calculations made it possible to determine the parameters of the TM aggregated via the rear three-point hitch of the MEV-115 “Autotraktor”. In

particular, it was established that the distance from the centre of mass of the TM to the rear axle varied from 0 to 4 m, and the TM weight ranged from 6.7 to 95 kN. For instance, with a TM weight of 20 kN and a 3 m distance between its centre of mass and the rear axle, the front axle load decreased from 20.2 to 2.01 kN, while the rear axle load increased from 13.8 to 52 kN.

Under conditions of uniform axle loading, the distance from the TM's centre of mass to the rear axle ranged from 0 to 4 m, and the TM weight ranged from 6.39 to 1.87 kN. The limiting factor for the TM weight was the minimum required front axle load of the MEV, needed to ensure controllability of the aggregate during transport movements, which had to be at least 20% of the total weight of the MTA. Under such conditions, with a TM weight of 12 kN, the minimum required front axle load of the MEV was 9 kN.

Future research will focus on other TM installation zones on the “Autotraktor” – type MEV, including the front, inter-axle, and frame-mounted zones. The results of these researches will enable the analysis of TM parameters in these zones and the justification of their application.

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CONFLICT OF INTEREST

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Валерій Адамчук

Доктор технічних наук, професор, академік
Інститут механіки та автоматики агропромислового виробництва
Національної академії аграрних наук України
08631, вул. Вокзальна, 11/1, смт Глеваха, Київська обл., Україна
<https://orcid.org/0000-0003-0358-7946>

Сергій Погорілий

Доктор технічних наук
Інститут механіки та автоматики агропромислового виробництва
Національної академії аграрних наук України
08631, вул. Вокзальна, 11/1, смт Глеваха, Київська обл., Україна
<https://orcid.org/0000-0002-9701-2678>

Віктор Присяжний

Кандидат технічних наук
Інститут механіки та автоматики агропромислового виробництва
Національної академії аграрних наук України
08631, вул. Вокзальна, 11/1, смт Глеваха, Київська обл., Україна
<https://orcid.org/0000-0001-5096-3241>

Вадим Яременко

Кандидат технічних наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0000-0002-3271-6287>

Валерій Мірний

Аспірант
Інститут механіки та автоматики агропромислового виробництва
Національної академії аграрних наук України
08631, вул. Вокзальна, 11/1, смт Глеваха, Київська обл., Україна
<https://orcid.org/0000-0003-0560-2484>

Агрегатування мобільного енергетичного засобу типу «Автотрактор» із технологічним модулем

Анотація. Актуальність дослідження обумовлена необхідністю підвищення ефективності машинно-тракторного агрегату (МТА) як на тягово-привідних операціях, так і на транспортно-технологічних з обов'язковим забезпеченням безпеки під час експлуатації. Метою роботи було встановлення, експериментальним шляхом, впливу маси ТМ на навантаження на осі мобільного енергетичного засобу (МЕЗ) типу «Автотрактор» під час агрегатування на задньому навісному пристрої. Розглянуто проблему стійкості та розподілу навантажень у МТА, зокрема МЕЗ типу «Автотрактор» на базі вантажних автомобілів підвищеної прохідності. Представлено розроблений в Інституті механіки та автоматики агропромислового виробництва Національної академії аграрних наук України багатофункціональний мобільний енергетичний засіб МЕЗ 115 «Автотрактор», що мав унікальні конструкційні рішення, зокрема централізовану систему контролю тиску повітря в шинах, гідравлічну систему, систему агрегатування ТМ на раму та спеціально розроблену та виготовлену задню навісну систему. Конструкція навісної системи МЕЗ типу «Автотрактор» забезпечувала агрегатування ТМ масою до 2 т. Компактне розміщення навісної системи на машині дозволяло безперешкодне агрегатування ТМ на рамі без демонтажу навісної системи. Проведено експериментальні дослідження за допомогою тензометричних ваг для перевірки теоретичних розрахунків розподілу навантажень на осі МЕЗ типу «Автотрактор» залежно від ваги та координати центру мас ТМ. Визначено критичні параметри ваги ТМ, які забезпечують безпечну експлуатацію МТА: відстань від центру мас ТМ до осі задніх коліс (0-4 м) та вага ТМ (6,39-18,7 кН). Встановлено параметри ТМ, які забезпечують рівномірне навантаження на осі, що у свою чергу унеможливило виникнення паразитної потужності між осями МЕЗ 115 типу «Автотрактор». Встановлено мінімально необхідне навантаження на передню вісь для забезпечення керованості МТА при переїздах, яке повинно становити не менше 20 % загальної ваги МТА. Результати дослідження підтверджують достовірність теоретичних моделей та показали ефективність описаної теорії. Отримані дані можуть бути використані для вдосконалення конструкцій МЕЗ та оптимізації параметрів у сільськогосподарському виробництві

Ключові слова: методи проведення експериментальних досліджень, вимірювальна техніка, калібрування датчиків, автотрактор, мобільний енергетичний засіб (МЕЗ)

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Saurabh Mehta*

PhD in Electronics and Telecommunications, Professor
Vidyalankar Institute of Technology
400037, Wadala (East), Mumbai, India
<https://orcid.org/0009-0006-9549-8842>

Riya Modi

Master of Biomedical Engineering, Research Student
Johns Hopkins University
MD 21218, 3400N Charles Str., Baltimore, USA
<https://orcid.org/0009-0003-4933-7966>

Pavlo Herasymenko

PhD in Technical Sciences, Senior Researcher
Institute of Electrodynamics of the National Academy of Sciences of Ukraine
03057, 56 Beresteyskyi Ave., Kyiv, Ukraine
<https://orcid.org/0000-0001-6244-1133>

Sergii Usenko

PhD in Technical Sciences, Associate Professor
National University of Life and Environmental Sciences of Ukraine
03041, 15 Heroiv Oborony Str., Kyiv, Ukraine
<https://orcid.org/0000-0001-7225-9589>

Exploring novel architectural elements and design concepts for wireless sensor nodes: A case study

Abstract. Wireless Sensor Networks (WSNs) play a crucial role in modern communication systems, enabling efficient data collection and transmission across various domains. These networks are pivotal in applications such as environmental monitoring, industrial automation, smart cities, and healthcare systems, where real-time and accurate data is essential. The purpose of this study was to develop and validate a novel wireless sensor node architecture for gas sensing applications, with a focus on improving energy efficiency, communication reliability, modularity, and adaptability to diverse environments. The proposed design integrated multiple radio chips, a stack-based architecture, and directional antennas to improve communication robustness and adaptability. A current driver circuit was introduced to mitigate sensor saturation, ensuring accurate gas concentration measurements. The stack-based architecture enhanced modularity and scalability, facilitating seamless upgrades and compatibility with emerging technologies. Additionally, directional antennas and a dedicated medium access control protocol optimised communication efficiency and localisation accuracy. Experimental evaluations, conducted within advanced research facilities, validated the effectiveness of the proposed design under diverse environmental conditions. The hardware design approach presented in this paper focused on using low-cost, off-the-shelf components strategically integrated to deliver high functionality without increasing complexity or cost. The modular design also allows additional sensing features – such as temperature, humidity, or particulate matter detection – to be incorporated easily and economically. The results demonstrated significant improvements in data transmission reliability, power consumption optimisation, and sensor longevity. The system achieved a favourable balance between performance

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*Corresponding author



and affordability, making it highly suitable for scalable deployment in resource-constrained settings. This work contributes to the advancement of WSN-based gas monitoring by addressing critical challenges in hardware selection, communication efficiency, and adaptive sensor operation. The architecture presents a promising solution for deployment in dynamic and harsh environments where traditional systems may fail

Keywords: hardware platforms; node design; patch directional antenna; transceiver; microcontroller; wireless sensor network

INTRODUCTION

In the era of ubiquitous connectivity and data-driven decision-making, wireless sensor networks (WSNs) have emerged as a transformative technology with diverse applications, ranging from environmental monitoring and precision to healthcare and industrial automation. By enabling efficient data collection and processing from the physical world, WSNs have fundamentally reshaped numerous domains. Their ability to operate in remote, hazardous, or inaccessible environments has expanded the scope of real-time monitoring and intelligent control in both civil and industrial contexts (Divyansh *et al.*, 2019).

As shown by A. Bhat & A. Passi (2022) and L. Gong *et al.* (2021), at the core of these networks are wireless sensor nodes, commonly referred to as “motes”; which function as the essential building blocks of WSNs. These motes typically comprise sensing units, microcontrollers, radio transceivers, and power sources, all designed to function cohesively under constrained energy and processing conditions. Their modularity and scalability enable flexible network topologies and dynamic data routing mechanisms, making them suitable for a wide variety of deployment scenarios. Innovations in low-power electronics, adaptive protocols, and integrated sensing technologies have further enhanced the performance and reliability of these systems. WSNs have become integral to modern communication systems, facilitating efficient data collection and transmission across various domains, and serving as a backbone for emerging technologies such as the Internet of Things (IoT) and cyber-physical systems.

Y. Singh & T. Walingo (2024) developed an IoT-based wireless sensor network for real-time water quality monitoring, highlighting its effectiveness in detecting key parameters such as pH, turbidity, and dissolved oxygen. Their study demonstrated that integrating low-power sensors with cloud platforms ensures scalable and efficient environmental monitoring. Researches Y. Luo *et al.* (2024) proposed a novel system enabling simultaneous wireless power and data transmission in full-duplex mode for underwater sensor networks. The research confirmed that this approach significantly improves communication reliability and extends operational lifetime in challenging aquatic environments.

As F. Busacca *et al.* (2024) suggested the choice of microcontroller plays a crucial role in WSN design, directly impacting performance and energy efficiency. Microcontrollers like the ATmega128L and MSP430F1611 offer enhanced node capabilities, especially when paired with larger EEPROM sizes to accommodate growing storage

demands. In addition, transceivers such as the Chipcon CC1000 and CC2420 enable high-data-rate applications, including audio and video transmission. Furthermore, integrating the TinyOS operating system, widely recognised in the literature; enhances compatibility and flexibility, ensuring seamless deployment in diverse WSN applications.

A. Thakkar *et al.* (2020) provided a broad classification of power management strategies in WSNs, emphasising dynamic voltage scaling, duty cycling, and cross-layer optimisation techniques as key drivers of energy efficiency. T. Mekonnen *et al.* (2017) explored energy consumption in multimedia sensor networks, underscoring the challenges posed by high data rates and suggesting architectural adaptations for multi-tiered node structures. Meanwhile, M. Amjad *et al.* (2016) reviewed the evolution of the TinyOS platform, highlighting its modularity, low overhead, and support for diverse sensing tasks, which makes it a favourable OS for constrained WSN environments.

In light of these findings, the current research builds upon a solid body of work in energy-aware design and system reconfigurability, proposing a wireless sensor node architecture optimised for gas detection. By synthesising advancements in operating systems, hardware modularity, and adaptive energy management, the proposed system is positioned to overcome existing limitations in scalability, environmental adaptability, and long-term deployment sustainability. The aim of this study was to design a wireless sensor network tailored for gas sensing applications, specifically intended to monitor and manage concentrations of hazardous gases. Through a thorough analysis of a specific case study, this paper highlights the innovative approach of selecting optimal hardware platforms, a critical factor in building robust and efficient WSNs.

MATERIALS AND METHODS

This study developed a comprehensive test setup to evaluate the performance and reliability of the wireless sensor node design incorporating methane (MQ4) and carbon monoxide (MQ7) gas sensors. The MQ4 and MQ7 sensors used in this setup were sourced from Winsen Electronics India Pvt. Ltd., a leading supplier and distributor of semiconductor-based gas sensors in India during 2012-13. These sensors are known for their affordability, easy interfacing, and widespread use in academic and industrial research. The MQ4 sensor is capable of detecting methane concentrations ranging from 200 to 10,000 ppm, with a typical sensitivity ratio (R_s/R_o) in clean air of ~4.4, and operates effectively within a temperature range of -10°C to

50°C. The MQ7 sensor, designed for carbon monoxide detection, operates in a range of 20 to 2,000 ppm, with an Rs/Ro ratio of ~1.5 in clean air, and features dual heater voltage operation (high and low cycles) to improve selectivity. The experiments were conducted within the advanced research facilities at the Indian Institute of Technology Bombay (IIT Bombay). The key objective was to assess the system's response to environmental factors and evaluate the effectiveness of innovative design modifications, such as the current driver circuit and stack-based architecture. The testbed ensured controlled gas exposure, precise timing of sensor activation, and real-time data logging to comprehensively analyse sensor behaviour and node-level performance under dynamic conditions. Figure 1 shows the experimental sensor node testbed, which includes sensor nodes integrated with gas sensors, a microcontroller ATmega128L (manufactured by Microchip Technology), and a Radio Frequency (RF) transceiver, providing real-time data for analysis.



Figure 1. Experimental sensor node testbed at IITB Lab, Mumbai

Source: photo by the authors

The wireless sensor node's block diagram (Fig. 2) represents the core components used in the experimentation, including gas sensors, microcontroller, battery, RF transceiver, and actuator. The sensors used in the test setup were calibrated and subjected to various environmental conditions to ensure their accuracy and reliability. To simulate real-world deployment scenarios, the test environment was carefully controlled and included variations in temperature (ranging from 10°C to 45°C) and relative humidity (ranging from 30% to 85%). The gas concentrations introduced in the test chamber included methane levels between 200 ppm and 5,000 ppm for the MQ4 sensor and carbon monoxide levels between 50 ppm and 1,000 ppm for the MQ7 sensor. These ranges were selected to reflect both typical indoor air quality levels and potential industrial leakage scenarios. Environmental chambers equipped with humidity and temperature controls were used to evaluate the sensor node's performance under fluctuating and extreme conditions. The calibration process involved

exposing the sensors to known gas concentrations and recording sensor response curves to ensure linearity and repeatability. Additionally, the impact of cross-sensitivity and sensor saturation was assessed under high concentration conditions. These rigorous environmental tests enabled a thorough validation of the sensor node's robustness, response time, and accuracy in detecting target gases, thereby supporting the system's viability for real-world deployment in diverse and dynamic conditions (Yokoyama *et al.*, 2024).

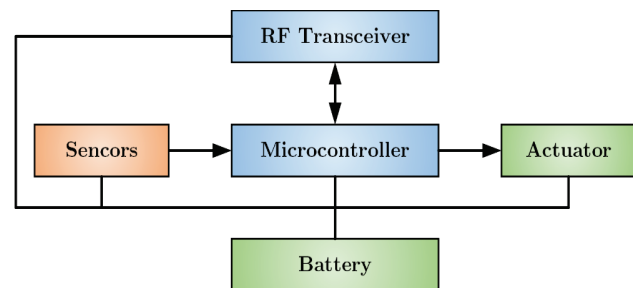


Figure 2. Typical block diagram of a mote

Source: compiled by the authors

Special focus was placed on using a current driver circuit to prevent sensor saturation, where the operating current of the sensors was dynamically adjusted, ensuring optimal performance. The heating elements integrated into the circuit enabled periodic recovery of the sensors to ensure their longevity and prevent damage from high gas concentrations. The wireless sensor node's stack-based architecture formed a critical aspect of the study, allowing for the integration of multiple radio chips for redundancy and improved communication capabilities. The node was designed with multiple radio chips to enable parallel data transmission, improving throughput and system reliability. The system was tested under various interference and environmental conditions to evaluate its adaptability and robustness. A total of 40 test iterations were performed, encompassing both hardware-level functionality and sensor communication reliability across a range of deployment scenarios. Modifying layers and radio chips assessed the modularity and scalability of the stack architecture to accommodate emerging technologies and future communication standards. During the testing process, the sensors were subjected to controlled gas exposure at multiple concentrations – methane (MQ4) at 200, 500, 1000, 3000, and 5000 ppm, and carbon monoxide (MQ7) at 50, 200, 500, and 1000 ppm. These tests were conducted under regulated environmental conditions, with temperature varying from 10°C to 45°C and humidity from 30% to 85%, to ensure comprehensive performance evaluation under both nominal and extreme conditions. These test iterations helped validate the effectiveness of the stack-based design in maintaining communication integrity and sensing accuracy under real-world challenges such as RF interference, fluctuating environmental factors, and variable sensor loads.

Additionally, the sensor nodes were equipped with directional antennas, optimised for energy-efficient communication and localisation. The antennas were tested for transmission range, signal quality, and interference reduction. The results were compared under different directional configurations to determine the most efficient setup for varying operational environments. The integration of the directional MAC layer played a crucial role in enhancing the communication efficiency of the system. The system's overall performance, including power consumption, data throughput, and

communication reliability, was analysed to provide a comprehensive understanding of the sensor node's capabilities.

RESULTS AND DISCUSSION

Developing a wireless sensor node incorporating multiple radio chips, directional antennas, a dedicated MAC protocol, and on-air programming represents a promising and innovative direction for future research and development. Table 1 summarises the gaps in existing hardware and commercially available nodes (Maia et al., 2009).

Table 1. Summarising the gaps in existing hardware and commercially available nodes

No.	Particulars		Motes	Features	Limitations	Remarks	Proposed Note
1.	Microcontroller						
1.1	Atmel AT 90LS8535		WeC, Rene 1	Clock 4 MHz RAM/Flash-512/8k	8 bit		
1.2	Atmel Atmega 163		Rene 2 Dot	Clock -8 MHz RAM/Flash-1K/16K			
1.3	Atmel Atmega128 L	Mica, BT Node, Mica 2 Dot, iBadge CENS Medusa MK2, Nymph, MicaZ, AquisGrain, DSYS 25, Ember RF Module, Module, Fleck		Clock 8 MHz RAM/Flash-4K/128K		Most popular among motes	Proposed
1.4	Atmel AT91FR40162S	Sunspot		Clock -75 MHz Flash-256K	%	32bit (Suitable for sink)	
1.5	TI MSP430F1611	Telos B/ TmoteSky, eyesIFXv2, SHIMMER		Clock -8 MHz Flash/EEPROM-10 K		16 bit (Lowest power consumption)	Proposed
2	External Memory						
2.1	EEPROM 32K		WeC, Rene 1, Rene 2, Dot				
2.2	EEPROM 48 K		Telos B/ TmoteSky, eyesIFXv2, SHIMMER				
2.3	EEPROM 512 K		Mica, BT Node, Mica 2 Dot, iBadge CENS Medusa MK2, Nymph, MicaZ, AquisGrain, DSYS 25, Ember RF Module, Module, Fleck				
2.4	EEPROM 2M		Sunspot				
3	Radio Transceiver						
3.1	RFM TR 1000		WeC, Rene 1, Rene 2, Dot Mica	BW (Kbps)-10 Freq (MHz)-900	Low Data Rate		
3.2	Chipcon CC		BT Node, Mica2, Mica2 Dot, Nymph	BW (Kbps)-38.4 Freq (MHz)-900			Proposed
3.3	Chipcon CC 2420		Telos, MicaZ,BSN Node, AquisGrain, Pluto, iMote 2, XYZ Sensor Node, ProSepKz II	BW (Kbps)-250 Freq (MHz)-2400		High Data rate Application audio	Proposed
4	Operating System						
4.1	Tiny Os		WeC, Rene 1, Rene 2, Dot Mica, BT Node Spot ON,Telos, Mica 2, Mica2 Dot, iMote. Spec, MicaZ,CIT Sensor Node, BSN Node, AquisGrain, Telos B/ TmoteSky			Most popular among motes	Proposed
4.2	Squawk VM (Java)		Sunspot				
5	Multiple Radio chip						
		Not Present					
6	Directional Antenna & MAC Protocol						Proposed
		Not Present					
7	On Air programming						Proposed
		WeC					Proposed

Source: developed by the authors based on M. Johnson et al. (2009)

As shown in Table 1, microcontrollers and transceivers are essential components of any communication system, and their selection must be based on theoretical principles to optimise system performance. For instance, a microcontroller should be selected based on processing speed, power consumption, peripheral support, and application requirements. Key theoretical factors to consider include the microcontroller's clock speed and architecture (e.g., RISC vs. CISC), power consumption analysis, and the availability of integrated peripherals such as analog-to-digital and digital-to-analog converters, and communication interfaces. As described in R. Qi & R. Li (2022) the Transceivers, responsible for transmitting and receiving data, are chosen based on factors such as frequency range, modulation techniques, and sensitivity.

Block diagram of the designed mote. Figure 3 shows a block diagram of the designed mote, highlighting the evolution of the wireless sensor node architecture. This design departs from the traditional actuator by introducing a current driver as an innovative replacement. This modification enhances the node's functionality, enabling the generation of pulsating signals in response to specific contextual conditions.

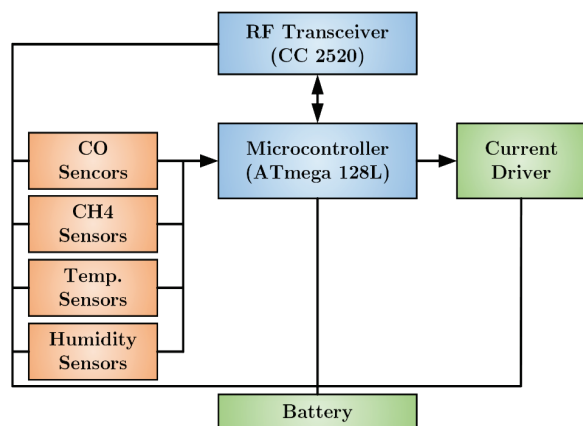


Figure 3. Block diagram of a designed mote

Source: compiled by the authors

To illustrate this concept, consider the operation of a gas sensor within the system. When activated, the gas sensor initiates the heating element, facilitating the detection of gases such as methane. A blade-in-sensor mechanism precisely manages gas deposition, converting it into an electrical signal. However, when exposed to excessive gas concentrations, the sensor risks oversaturation, leading to an increase in output values. This phenomenon not only signals potential saturation but also enriches the dataset with valuable insights.

A key innovation in this architecture is the integration of a current driver. By generating controlled pulsations, the current driver enhances the sensor node's ability to respond dynamically to environmental changes, improving accuracy and adaptability (Fig. 4). The block diagram of the designed mote in Figure 3 visually represents this concept, emphasising the role of the current driver.

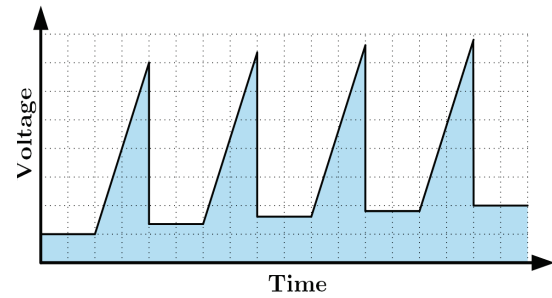


Figure 4. Current driver waveform

Note: gas sensor saturation

Source: compiled by the authors

Gas sensors can become saturated when exposed to high concentrations of the target gas, resulting in inaccurate readings or potential damage to the sensor. To mitigate this issue, various strategies are employed, including gas dilution, the utilisation of alternate sensors, periodic calibration, controlled sampling, physical protection, automatic shutdown, remote control, robust sensor design, data analysis, and regular maintenance. F. Ricciardella *et al.* (2017) proposed a novel strategy to address saturation and recovery delays in CVD (chemical vapor deposition) graphene-based gas sensors by applying pulsed heating and interface engineering. Their results showed enhanced response times and greater stability of the sensors under high gas concentration conditions. Scientists C. Ezeigweneme *et al.* (2024) investigated the role of wireless communication in electro-mechanical systems, focusing on the transition to cordless interfaces. They demonstrated that such technologies improved system modularity, reduced interference, and enhanced the adaptability of hardware configurations.

A highly effective approach to preventing gas sensor saturation is the integration of a current driver circuit. This circuit dynamically adjusts the sensor's operating current, optimising its sensitivity and preventing saturation. Additionally, it incorporates heating elements that can be selectively deactivated, allowing the sensor to recover and maintain accuracy for subsequent readings. This design ensures reliable gas detection, particularly in high-concentration environments, increasing both the sensor's longevity and performance. By integrating these approaches, sensor saturation risks are effectively mitigated, ensuring precise and reliable monitoring of hazardous gas concentrations within the wireless sensor network.

Stack architecture. As B. Aghaei (2011) and S. Petersen *et al.* (2007) have shown in their work without any stack-based approach, the second key feature distinguishing in current study designed wireless sensor node is its stack-based architecture – a transformative approach that significantly enhances the node's capabilities and versatility. Unlike conventional designs, this architecture enables the seamless integration of multiple radio chips within a single node, introducing greater flexibility and adaptability. Even P. Bekal *et al.* (2024) have adopted the stack-based

architecture with a layered system design, promoting modularity, ease of debugging, and scalability. By partitioning the system into distinct layers, each responsible for specific functions, it minimises interdependencies, ensuring that modifications in one layer have minimal impact on others. This enhances maintainability and facilitates incremental upgrades. Moreover, incorporating multiple radio chips leverages parallel processing and redundancy, improving both robustness and performance. Backup communication channels enhance reliability, while load balancing optimises throughput. The ability to transmit and receive data simultaneously across different frequencies reduces latency and increases efficiency.

This architecture aligns with the open systems interconnection model by M. Kaddi *et al.* (2024), which provides a conceptual framework for network interactions across seven layers. Key advantages include: 1) modularity – independent operation of each layer allows targeted upgrades and efficient troubleshooting; 2) interoperability – standardised interfaces ensure compatibility with diverse hardware and software components; 3) scalability – new functionalities can be easily incorporated by adding or modifying layers (Mazin & Onykienko, 2023). Figure 5 illustrates the stack designed in this study. The stack architecture's contribution extends beyond its immediate functionality, significantly enhancing the node's scalability by accommodating multiple radio chips. The node can quickly adapt to evolving communication standards and emerging technologies. This future-proofing feature safeguards investments and ensures the node remains relevant in the dynamic landscape of technological advancements.

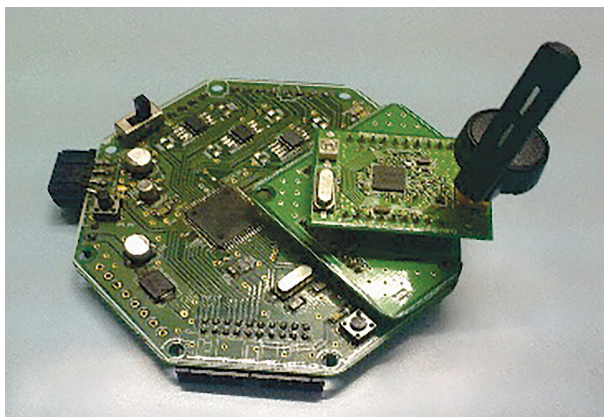


Figure 5. Stack design

Source: photo by the authors

Integrating a stack-based architecture within the wireless sensor node introduces a new dimension of communication capabilities (Fig. 6). This innovation improves the node's ability to interact, collaborate, and contribute within wireless sensor networks. By leveraging the advantages of layered integration, the stack architecture exemplifies adaptability and potential, paving the way for new opportunities in wireless communication technology.

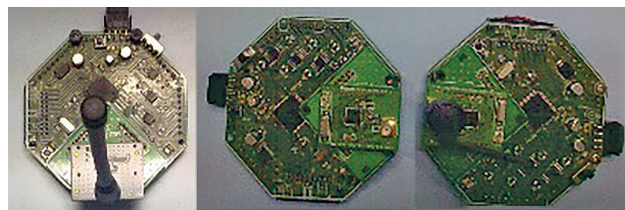


Figure 6. WSN of designed nodes

Note: node design using multiple directional antennas for localisation

Source: compiled by the authors

Another key feature of the wireless sensor node is the directional antenna, which enhances energy efficiency by optimising radiation directivity. As M. Shah & S. Mehta (2013) and S. Kasar *et al.* (2013), review key localisation techniques in wireless sensor networks, categorising them into range-based and range-free methods. It analyses algorithms like RSSI, ToA, AoA, and DV-Hop, discussing their trade-offs in terms of cost, accuracy, and complexity. The authors highlight real-world challenges and suggest directions for improving localisation efficiency and precision in future research. This approach marks a shift in antenna design, focusing on improving signal propagation and reception patterns. While testing is still ongoing, the potential benefits are promising. These antennas are expected to offer enhanced transmission range, reduced interference, and improved signal quality by directing radiation toward specific areas.

The node's architecture includes provisions to support up to six directional antennas (Fig. 7), offering significant versatility to meet the dynamic needs of various applications. This modularity allows the node to customise its antenna configuration for specific scenarios, optimising communication paths and enabling adaptive responses. Central to this capability is the development of an advanced localisation algorithm, which is essential for providing precise spatial awareness, enabling the node to accurately determine its position relative to neighbouring nodes.

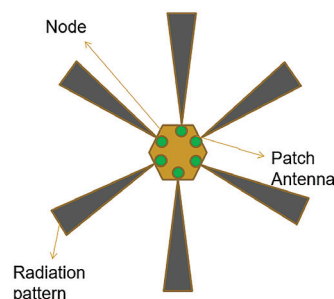


Figure 7. Directional antenna

Source: compiled by the authors

The directional antenna design is closely integrated with the development of a directional MAC layer. This layering strategy facilitates efficient channel access, reducing

contention and collisions while enhancing communication efficiency. The synergy between the directional antennas and the MAC layer forms a powerful combination, improving energy conservation and communication reliability. The node's design incorporates a scheme that leverages the collective potential of multiple directional antennas for precise localisation.

M. Shah & S. Mehta (2013) reviewed key hardware platforms for wireless sensor networks, comparing options

like MICA, TelosB, and IRIS. It highlights trade-offs in processing power, energy use, memory, and cost, emphasising the need for modular and energy-efficient designs suited to specific applications. This paper highlights the key innovations and features of the mote design. Additionally, the limitations and challenges encountered during experimentation are examined, along with potential solutions and future directions. A comprehensive summary of the research and its implications is provided in Table 2.

Table 2. Summary of the research and its implications

Limitation/Challenge	Description	Potential solutions
Power consumption	High power usage reduces node lifespan.	Low-power components, energy-efficient protocols, energy harvesting (solar, kinetic).
Processing and memory constraints	Limited processing power and memory restrict complex algorithms.	Optimise algorithms, use lightweight data compression, and offload tasks to the central server/edge device.
Communication range and reliability	The range is limited by antenna design, transmission power, and obstacles.	Mesh networking, additional nodes/repeaters, adaptive communication protocols.
Environmental factors	Performance and longevity are affected by temperature, humidity, and obstructions.	Robust materials, calibration routines, and adaptive systems.
Cost constraints	Keeping costs low can compromise performance and reliability.	Careful component selection, economies of scale, and cost-sharing models.
Scalability	Ensuring performance with a large number of nodes.	Hierarchical architectures, efficient routing protocols, dynamic network management.
Data security and privacy	Securing data transmission and ensuring privacy.	Strong encryption, secure key management, and protective protocols against eavesdropping/ data tampering.
Synchronisation	Maintaining time synchronisation across all nodes.	Time synchronisation protocols (IEEE 1588 PTP, NTP), periodic re-synchronisation.
Interference and coexistence	Potential interference from other wireless devices.	Interference mitigation techniques (frequency hopping, adaptive channel selection), coexistence protocols.
Node deployment and maintenance	Difficult deployment in large/inaccessible areas and logistical maintenance challenges.	Autonomous deployment (drones/robots), self-healing/self-organising networks, remote maintenance and diagnostics tools.

Source: compiled by the authors

Table 2 summarised the key challenges faced in designing and deploying WSNs, including high power consumption, limited processing and memory capabilities, and restricted communication range. Environmental factors like temperature and humidity also impact node reliability and lifespan. To address these, solutions such as low-power components, energy harvesting, and robust calibration mechanisms are suggested. Cost remains a major constraint, often requiring a careful balance between performance and affordability. Scalability and synchronisation become critical as networks grow, necessitating hierarchical designs and time synchronisation protocols. Ensuring data security and privacy is another priority, tackled through encryption and secure key management. Additionally, interference from other wireless devices and the complexity of node deployment in remote areas pose ongoing challenges. Mitigation techniques include adaptive communication, autonomous deployment methods, and self-healing networks.

CONCLUSIONS

This study presents a novel wireless sensor node architecture specifically designed for gas sensing applications, focusing on key challenges such as energy efficiency,

communication reliability, and system adaptability. The proposed design integrates multiple radio chips, a modular stack-based hardware architecture, and directional antennas to significantly enhance performance in dynamic environments. The inclusion of a current driver circuit effectively addresses the issue of sensor saturation, thereby improving the accuracy of gas concentration measurements even under fluctuating environmental conditions. The stack-based design promotes scalability and modularity, allowing for seamless integration of emerging technologies and easier customisation for various application domains.

In addition, the use of directional antennas and a dedicated medium access control layer helps optimise communication efficiency, improve signal strength, and support enhanced node localisation – critical for applications such as hazardous gas leak detection and environmental monitoring. The system was rigorously tested across a range of environmental conditions, including variations in temperature, humidity, and gas concentrations, to evaluate its robustness and reliability. Experimental results confirm improvements in data transmission accuracy, power consumption, and overall system longevity.

The architecture also supports the integration of additional sensors and communication modules at a low cost,

making it a viable solution for large-scale deployments. This work contributes to advancing WSN-based gas monitoring systems by addressing fundamental hardware challenges and proposing a cost-effective, energy-conscious, and future-ready solution. Future work will focus on refining real-time data processing, enhancing interference resilience, and enabling broader field deployments in industrial and urban settings.

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CONFLICT OF INTEREST

None.

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Саурабх Мехта

Доктор філософії з електроніки та телекомунікацій, професор
Технологічний інститут Від'яланкар
400037, район Вадала (східна частина), м. Мумбай, Індія
<https://orcid.org/0009-0006-9549-8842>

Рія Моді

Магістр біомедичної інженерії, дослідник
Університет Джонса Гопкінса
MD 21218, вул. Чарлза, 3400N, м. Балтімор, Сполучені Штати Америки
<https://orcid.org/0009-0003-4933-7966>

Павло Герасименко

Кандидат технічних наук, старший науковий співробітник
Інститут електродинаміки Національної академії наук України
03057, просп. Берестейський, 56, м. Київ, Україна
<https://orcid.org/0000-0001-6244-1133>

Сергій Усенко

Кандидат технічних наук, доцент
Національний університет біоресурсів і природокористування України
03041, вул. Героїв Оборони, 15, м. Київ, Україна
<https://orcid.org/0000-0001-7225-9589>

Дослідження нових архітектурних елементів і концепцій проектування для бездротових сенсорних вузлів: приклад з практики

Анотація. Бездротові сенсорні мережі відіграють важливу роль у сучасних системах зв'язку, забезпечуючи ефективне збирання та передавання даних у різних сферах. Такі мережі є ключовими для застосувань, пов'язаних із моніторингом довкілля, промисловою автоматизацією, розумними містами та системами охорони здоров'я, де критично важливими є точні й оперативні дані. Метою цього дослідження було розробити та перевірити нову архітектуру бездротового сенсорного вузла для задач газової детекції з акцентом на підвищення енергоефективності, надійності зв'язку, модульності та адаптивності до різноманітних умов експлуатації. Запропонована конструкція поєднує використання декількох радіочіпів, архітектури на основі стеку та спрямованих антен для підвищення стійкості до зовнішніх впливів і адаптивності мережі. Для запобігання насиченню сенсора було введено схему струмового драйвера, що забезпечує точність вимірювання концентрації газів. Архітектура на основі стеку покращує модульність і масштабованість, спрощуючи оновлення та забезпечуючи сумісність із новітніми технологіями. Крім того, спрямовані антени та спеціалізований протокол доступу до середовища підвищують ефективність зв'язку та точність локалізації. Експериментальна перевірка, проведена в сучасних наукових лабораторіях, підтвердила ефективність запропонованої конструкції в умовах різноманітного середовища. Представлений підхід до розробки апаратної частини базується на використанні недорогих, масово доступних компонентів, інтегрованих таким чином, щоб забезпечити високу функціональність без збільшення складності або вартості. Модульна конструкція також дає змогу легко та економно додавати додаткові сенсорні функції, наприклад, вимірювання температури, вологості або концентрації частинок. Результати показали суттєве покращення надійності передавання даних, оптимізацію енергоспоживання та збільшення довговічності сенсорів. Система досягла оптимального балансу між продуктивністю та доступністю, що робить її придатною для масштабованого розгортання в умовах обмежених ресурсів. Це дослідження робить внесок у розвиток газового моніторингу на основі бездротової сенсорної мережі шляхом вирішення ключових викликів у виборі апаратного забезпечення, ефективності зв'язку та адаптивної роботи сенсорів. Запропонована архітектура є перспективним рішенням для розгортання в динамічних та суворих умовах, де традиційні системи можуть виявитися неефективними.

Ключові слова: апаратні платформи; конструкція вузлів; спрямована патч-антена; приймально-передавальний пристрій; мікроконтролер; бездротова сенсорна мережа

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Vasyl Hruban*

PhD in Technical Sciences, Associate Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0003-0753-565X>

Antonina Drobitko

Doctor of Agricultural Sciences, Professor
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-6492-4558>

Mykyta Khramov

Assistant
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0000-0002-2537-7344>

Maksym Tovpyha

Postgraduate Student
Mykolaiv National Agrarian University
54008, 9 Georgiy Gongadze Str., Mykolaiv, Ukraine
<https://orcid.org/0009-0009-5958-8359>

Strength analysis and optimisation of trailer agricultural machinery structures using finite element methods

Abstract. The aim of the study was to examine the potential of numerical modelling for improving agricultural machinery by analysing its characteristics and technological features. A theoretical analysis was carried out using theoretical modelling, which allowed for the evaluation of stress-strain states of the machinery under different loads. It was found that numerical modelling reduced the weight of machinery by removing excess material in low-stress zones and also decreased emissions through improved geometry of working components, which contributed to energy savings and increased operational efficiency. It was revealed that modern technologies underestimated the potential of composite materials and nanotechnologies, which limited the achievement of higher strength, lightness, and durability indicators, while simplified models ignored variable climate factors, soil diversity, humidity, and temperature fluctuations, which affected wear and corrosion of the machinery. The study showed that agricultural machinery was subjected to dynamic, cyclic, vibrational, and impact loads, which caused fatigue failure of materials and local stresses, particularly in the areas of fastenings of working elements and hinged joints, which reduced service life and required improved materials. The results contributed to economic benefits for the agricultural sector through reduced fuel and maintenance costs, environmental sustainability through reduced emissions, and improved working conditions for operators by reducing vibrational loads. The results of the study could be used in the design and improvement of the structures of towed

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*Corresponding author



agricultural machinery, taking into account specific operating conditions, particularly for preliminary modelling and optimisation of the working elements of machines in agricultural regions with increased frame loads

Keywords: numerical modelling; stress-strain state; vibration loads; composite materials; energy efficiency; real conditions; agricultural machinery

INTRODUCTION

The topic of optimising the design of agricultural machinery was extremely relevant in the context of the modern development of the agricultural sector, where the demands for increased efficiency, reliability, and economic benefits of machinery were growing. Since agriculture was an important component of the economy of many countries, including Ukraine, the improvement of technical equipment used in this sector became a significant area of scientific research. However, traditional methods of machinery design often failed to take into account all the factors influencing its performance, which led to the need to apply new, more accurate methods for the analysis and optimisation of designs (Huseynov, 2024). One such method was the use of finite element methods (FEM), which allowed for the detailed study of the mechanical characteristics of structures and the behaviour under loads. This made it possible not only to assess the stability and strength of machinery, but also to optimise its design to reduce maintenance costs and decrease energy consumption.

Existing studies showed that the use of FEM could significantly improve the efficiency of agricultural machines, particularly tractors, combine harvesters, and other towed equipment, by reducing maintenance costs and extending the service life (Stavinskiy *et al.*, 2024). E.B. Aliiev *et al.* (2023) studied numerical modelling of the operation of a soil cultivation module, emphasising the importance of analysing vibrational loads to reduce mechanical stresses and improve machinery reliability. The findings contributed to the development of effective design solutions for agricultural machinery, particularly under conditions of uneven soil surfaces. The study by G. Filimonikhin *et al.* (2021) focused on analytical methods for balancing rotors in agricultural machines, helping to identify ways to reduce mechanical loads on rotor systems, positively impacting operational cost reduction and enhancing machine efficiency. This approach supported improved design solutions and reduced the need for costly maintenance. N. Veselovska *et al.* (2023) investigated the efficiency of modernised threshing units in grain harvesters. The authors proved that the improvement of working components allowed for a significant reduction in grain losses during harvesting and improved threshing quality, which contributed to increasing machine productivity. This study was important for optimising work processes and reducing material costs in agriculture.

The integration of modern technologies and materials was also essential for improving the efficiency of agricultural machines and supporting sustainable development in the agricultural sector through the implementation of

energy-efficient and economical solutions (Shvedchykova *et al.*, 2024). O. Savenkov *et al.* (2024a) analysed the impact of new joint constructions on the operational characteristics of agricultural machinery, highlighting the importance of such changes for improving the reliability of machinery and reducing maintenance costs. The work showed how the application of innovative joints could enhance the durability of machines, reducing breakdown frequency and the need for repairs, which directly affected the economic efficiency of agricultural enterprises. O. Bazaluk *et al.* (2021) identified the energy efficiency of inland water transport for agriculture in Ukraine. The research was an important component in optimising the transport of agricultural products via waterways. The use of water transport allowed for reduced transportation costs and CO₂ emissions, which was critical for ensuring the sustainable development of the agricultural sector (Rud, 2024). This approach contributed not only to resource savings, but also to improving the environmental situation in the region. In the study by A.G. Goncharuk *et al.* (2018), the market for alternative motor fuels for agricultural machinery in Ukraine was examined, with a focus on how the use of such fuels could significantly reduce energy consumption and fuel costs. This, in turn, supported the sustainable development of the agricultural sector by reducing environmental impact and costs, resulting in increased economic efficiency.

A. Voloshina *et al.* (2021) studied the prediction of changes in the output characteristics of planetary hydraulic motors, which was important for understanding the impact of hydraulic system parameters on the efficiency of agricultural machinery. The study allowed for improved management of energy consumption and machine productivity, which was a critical aspect for design optimisation. O. Ostapenko (2024) assessed the potential of using alternative energy sources for powering agriculture in Ukraine. The study also demonstrated how energy-efficient technologies could be integrated into the agricultural sector, reducing energy consumption costs and promoting sustainability. A. Panchenko *et al.* (2019) focused on the reliability of designs, particularly in the design of rotors for orbital hydraulic motors, which was fundamental for ensuring the stable operation of hydraulic systems in agricultural machines. The work contributed to reducing the risk of breakdowns and improving machine reliability, which was important for lowering maintenance costs.

However, there was a research gap concerning the integration of technologies under real conditions, particularly in the example of Ukraine, where not only technical aspects but also social and economic challenges were

important. Existing studies focused on individual system components, but not enough attention was given to a comprehensive approach to assessing the efficiency under the conditions of high instability of energy networks. The aim of the study was to conduct a theoretical analysis of the efficiency of applying FEM for optimising the design of towed agricultural machinery, particularly the frames of seeders, through numerical modelling of stress-strain states under operational loads.

MATERIALS AND METHODS

The research was conducted from September 2024 to January 2025 and involved the study of optimisation methods for the design of towed agricultural machinery using FEM. The research was theoretical in nature and considered the Educational, Scientific and Practical Centre of Mykolaiv National Agrarian University (ESPC MNAU) (Mykolaiv National Agrarian University, n.d.) as a potential research platform for the experimental validation of numerical modelling results, taking into account the centre's specialisation in practical testing of agricultural machinery and its location in a region with typical agricultural conditions. However, at the time of the study, experimental validation had not been carried out due to the lack of available data on testing of towed agricultural machinery under real conditions at ESPC MNAU, as well as limited access to information on the centre's current projects. Field trials had either not been conducted or had not been documented in open sources. The results obtained were hypothetical and applied in nature and required further experimental verification in real operational conditions.

The main focus was on modelling stress-strain states (SSS) to assess the impact of impact loads, which allowed for the identification of gaps in the use of composite materials, as well as the development of recommendations for increasing efficiency and durability of machinery, taking into account the principles of sustainable agricultural development. At the first stage, a systematisation of types of loads and examples of the application influencing towed agricultural machinery was carried out, including dynamic, cyclic, vibrational and impact loads. For this purpose, the content analysis method was used to review the studies by H.K. Celik *et al.* (2024), D.A.A. Esteban *et al.* (2024), J. He *et al.* (2024), which allowed the classification of loads based on the nature and impact on the SSS of structures.

The second stage of the research involved theoretical modelling of the SSS of towed seeder frames using FEM. The choice of towed seeders as the modelling object was due to the prevalence in Ukraine's agricultural sector and the significant impact of various loads on the structure during operation. A generalised model of a seeder frame was used for modelling, representing a typical structure with approximate geometric characteristics: a rectangular frame 4 m long, 2 m wide and with a profile height of 0.1 m, made of S355 steel (yield strength 355 MPa, modulus of elasticity 210 GPa). The model accounted for wheel mount zones and hinge joints as critical areas prone to stress

concentration. A tetrahedral mesh of finite elements was used for discretising the structure, with an average element size of 10 mm in high-stress zones (wheel mounts, hinges) and 20 mm in less loaded areas, resulting in approximately 50,000 nodes and 200,000 elements. Numerical methods, including equations for determining displacements and stresses implemented in FEM, made it possible to evaluate the maximum stresses and deformations in the specified zones, identify critical areas, and develop recommendations for the reinforcement, such as adding stiffening ribs or locally increasing material thickness.

At the third stage, an analysis of the advantages and limitations of FEM in technical modelling of agricultural machinery was carried out to assess the applicability of the method for design optimisation and identify areas for improvement. A data synthesis method was applied to integrate the findings from the studies by O. Savenkov *et al.* (2024b), J. Neuhäusler *et al.* (2024), J. Szusta *et al.* (2023) for evaluating the universality, accuracy, and computational costs of FEM and identifying its limitations. In addition, optimisation methods (topological, parametric, geometric) were analysed using content analysis of publications by B. Shan *et al.* (2024), A. Soleimani *et al.* (2024), J. He *et al.* (2024), which allowed for the integration of results to assess the effectiveness based on criteria such as weight reduction, emission reduction and improved energy efficiency, and for identifying gaps in modern agricultural machinery design. At this stage, a systems analysis was also applied to investigate the impact of optimisation methods on the social, economic and environmental aspects of the use of towed agricultural machinery in order to assess the potential for sustainable development of the agricultural sector.

To process sources, the bibliographic manager Zotero was used, which contributed to the systematisation of publications and thematic classification. For the theoretical modelling of SSS of towed seeder frames, ANSYS Mechanical software was used, providing highly accurate numerical modelling of stresses and deformations, allowing for a reliable assessment of the behaviour of structures under static and dynamic operational loads.

RESULTS AND DISCUSSION

The analysis of structural strength relied on classical theories (the theory of elasticity, the theory of strength of materials) formed in the 19th-20th centuries, which were based on the principles of continuum mechanics, including Hooke's law, equilibrium equations and strength criteria (Tresca, Mohr, Huber-von Mises) (Timoshenko, 1953; Bories & Schmidt, 2011). Modern approaches extended these principles by taking into account non-linear material properties, fatigue failure and complex loads (thermomechanical, vibrational, impact). The development of computer modelling, particularly FEM, enabled multifactorial studies and the identification of critical zones in structures that were difficult to determine using analytical methods (Celik *et al.*, 2024; Savenkov *et al.*, 2024a).

One of the key concepts in strength analysis was the stress-strain state (SSS), which described internal forces (stresses) and the corresponding displacements or deformations in a body under load (Fig. 1).

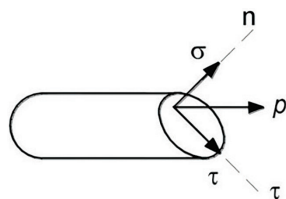


Figure 1. Stress and strain distribution diagram in a structural element of the cylindrical part of a mounted seed drill frame

Note: σ – normal stress, which acted perpendicular to the material surface (arising from tension or compression of the material), τ – shear stress, which acted along the surface and caused parts of the material to slide or shear relative to each other, p – the value indicating how strongly the structural element was bent (the smaller the radius, the greater the curvature), n – a vector indicating the direction normal to the surface of the structural element

Source: compiled by the authors

The stress and strain distribution diagram in the structural element of the cylindrical part of the frame of a trailed seed drill showed how internal forces and corresponding deformations were distributed across the structural element under the action of external loads. The stresses σ and τ demonstrated the internal forces arising under the loads on the structure. These forces were used to assess the strength of structures and to determine the ability to withstand loads without failure.

The calculation of the stress-strain state (SSS) made it possible to assess the suitability of the structure for operation under specified conditions. The equilibrium equations underlying the SSS analysis included: internal equilibrium

equations; geometric equations describing deformations; physical (constitutive) equations describing the relationship between stress and strain (e.g. linear elasticity or plasticity). In the context of trailed machinery, these equations acquired particular importance, as the structures were subject to variable, impact, and often asymmetric loads. For the solution, it was reasonable to use numerical methods that considered actual geometric and material characteristics. When modelling the SSS of the frame of a trailed seed drill using FEM, it could be found that the maximum stresses occurred in the wheel mounting zones due to impact loads from uneven soil surfaces. Reinforcing these zones by increasing the metal thickness or adding stiffening ribs could reduce the risk of deformation, confirming the importance of numerical methods for practical design (Bulgakov *et al.*, 2020).

Trailled agricultural machinery, such as seed drills, fertiliser spreaders and trailers for transporting crops, was characterised by structural features that affected the strength properties. These included lightweight metal frames of complex geometry, numerous welded, bolted and hinged joints, as well as operation in moist and abrasive environments (soil, dust, fertilisers) under variable loads depending on soil type, movement speed and tractor unit. These factors caused complex stress-strain states that contributed to fatigue failure, corrosion, and local stress concentrations. FEM allowed for the consideration of actual geometry and material properties by modelling the SSS of frames, weld seams or working elements, thus providing a basis for the optimisation. The operation of trailed machinery in field conditions differed significantly from industrial or road environments due to surface unevenness, varying soil characteristics and changing climatic factors. These conditions created a combination of loads affecting the durability and reliability of the structures. Table 1 summarised the main types of loads, examples, and the impact on the structure.

Table 1. Types of loads on trailed agricultural machinery under operating conditions

Load type	Description	Examples	Impact on the construction
Dynamic	Variable loads formed due to the movement of machinery over uneven surfaces, acceleration, braking, or transporting loads with varying mass and distribution, as well as from uneven force distribution at contact points with the soil and changes in movement speed	Movement across uneven fields with different soil types, transporting loads with uneven mass distribution, acceleration or braking on slopes	Increased stress in the frame, supporting elements, and joints, which caused a risk of plastic deformations, accumulation of residual stresses in concentration zones, and potential structural instability under prolonged exposure
Cyclic	Loads arising from repeated identical working cycles, associated with periodic movements of mechanisms, changes in operating modes, or switching between working phases, which created regular stress fluctuations in structural elements	Periodic lifting and lowering of working elements, rotation of spreading mechanisms, regular repositioning of components during operation	Initiation of fatigue failure due to gradual accumulation of microcracks, accelerated wear of moving joints, particularly hinges and bearings, and reduced strength in areas with high cyclic loading
Vibrational	Oscillatory loads transmitted to the structure through contact with uneven soil surfaces, wheel rotation, vibration from the tractor's power unit, or uneven mass distribution, which could lead to resonance phenomena when vibration frequencies matched the natural frequencies of the structure	Vibrations caused by uneven soil surfaces, wheels rotating at different speeds, transmission of vibrations from the tractor engine through joints	Occurrence of resonant oscillations increasing stress in welds and bolted joints, causing the loosening, increasing the risk of joint failure and leading to premature wear of structural elements due to dynamic fatigue

Continued Table 1.

Load type	Description	Examples	Impact on the construction
Impact	Short-term impulse loads occurring due to sudden changes in operating conditions, particularly when working elements encountered hard obstacles, sudden manoeuvres, or changes in the movement trajectory, creating local peak stresses in the structure	Impacts from contact with hard objects in the soil, sharp manoeuvres during movement, sudden changes in direction on uneven surfaces	Occurrence of local plastic deformations, formation of cracks in stress concentration zones, disruption of the structure's geometric integrity, and potential displacement or deformation of working elements, affecting the machinery's functionality

Source: compiled by the authors based on X. Sun *et al.* (2023), J. Szusta *et al.* (2023), D.A.A. Esteban *et al.* (2024), S. Hussain *et al.* (2024), J. He *et al.* (2024), H. Rahman & P. Sarkar (2024), H.K. Celik *et al.* (2024), J. Neuhäusler *et al.* (2024)

All these loads were characterised by variability in time and space, due to the unevenness of surfaces, diversity of soil conditions, changes in movement speed, and the influence of external factors such as humidity and temperature. This variability significantly complicated the construction of accurate analytical models for predicting structural behaviour under load. This, in turn, emphasised the relevance of using numerical methods, which made it possible to take into account the complex nature of loads, model the impact on the structure, and ensure its durability and reliability under real operating conditions. FEM (Finite Element Method) was a numerical method for solving complex physico-mechanical problems. It involved dividing a structure into simpler elements (triangles or tetrahedra), each with its own geometry and material properties. Each element was modelled separately, and the interaction was described through a system of equations. The method enabled effective solutions of strength, thermal conductivity, dynamics, fatigue, etc. In the context of agricultural machinery, it was especially useful due to its ability to account for variable loads, impact effects, and complex geometry of structures (Celik *et al.*, 2024). The solution of strength, thermal conductivity, or structural dynamics problems using FEM was based on a system of equations describing the interaction of the structure's elements. In general form, formula (1) appeared as follows:

$$K \times u = F, \quad (1)$$

where: K – stiffness matrix of the system (dependent on geometry and material properties), u – displacement vector of the structure's elements, F – vector of external loads.

To analyse stresses in structures under variable loads, formula (2) was used in conjunction with the constitutive material equations:

$$\sigma = C \times \epsilon, \quad (2)$$

where: σ – stress vector, C – material matrix (e.g., for elastic materials it included the modulus of elasticity), ϵ – strain vector.

These equations described the relationship between stress and strain in each element of the structure under a given load. To solve thermal conductivity problems arising in structures, it was necessary to consider heat flows between elements, which could be described by formula (3):

$$K_T \times T = Q, \quad (3)$$

where: K_T – thermal conductivity matrix, T – temperature vector at points of structural elements, Q – vector of external thermal loads. To analyse material fatigue caused by repeated loading, Miner's criterion was used:

$$\sum_{i=1}^n \frac{n_i}{N_i} = 1, \quad (4)$$

where: n_i – the number of load cycles that the element can withstand at a certain load level, N_i – the number of cycles required to achieve failure at the same load.

The FEM calculation process involved a number of key stages, each important for result accuracy and correct modelling. The first was discretisation – breaking the complex geometry into simpler elements. This could include triangulation, quadratic elements, or tetrahedra, depending on geometry complexity and required precision. The mesh quality was crucial: coarse meshes could lead to errors, while overly fine ones demanded significant computational resources. For each mesh element, local equilibrium equations were formulated, describing the relationship between forces, displacements, and stiffness. This was done using the standard formula (5) (Zienkiewicz *et al.*, 2013):

$$[K]\{u\} = \{F\}, \quad (5)$$

where: $[K]$ – element stiffness matrix, $\{u\}$ – displacement vector (unknown quantities), $\{F\}$ – vector of forces applied to the element.

This equation described deformation and structural response to loading on each element separately. After formulating equations for all system elements, the next stage was assembling the global stiffness matrix. All local stiffness matrices were combined into one global matrix describing the behaviour of the entire structure. This allowed the interaction of all elements to be accounted for and a single equation system to be built. This stage was critical for model validity, as changes to the stiffness of one element could affect the entire structure.

The third stage involved setting boundary conditions that defined how the structure interacted with its environment. This included defining fixed nodes (where displacement equalled zero) and applied forces, moments, or other loads. Boundary conditions could also reflect natural factors like temperature or humidity. The accuracy was crucial, as incorrect conditions could result in

imprecise outputs – especially for structures operating under cyclic or high-temperature conditions (Savenkov *et al.*, 2024b). Once the global system was formed, the next step was solving the system. The equations included unknown nodal displacements, which were solved using numerical methods (e.g., Gaussian method – direct solution; conjugate gradient method – iterative; LU decomposition – direct) (Zienkiewicz *et al.*, 2013). Once displacements were determined, other characteristics like stress or strain could be calculated. Based on the obtained nodal displacements, stress, and strain were calculated using standard theoretical equations. One such equation was formula (6):

$$\sigma = E \times (\varepsilon - \varepsilon_0), \quad (6)$$

where: E – modulus of elasticity of the material, ε_0 – initial deformation (or deformation in the absence of loads).

This enabled the identification of potential failure zones or areas exceeding permissible stress limits, which was critical for further design optimisation. The obtained results could also be used to assess structural reliability and its capacity to withstand long-term loads under real operating conditions. FEM offered opportunities to reduce structure weight, increase strength, and cut maintenance costs, which was particularly important for agricultural machines operating in variable and often harsh conditions. However, despite its many advantages, the method had limitations that needed to be considered (Table 2).

Table 2. Advantages and limitations of FEM in technical modelling of trailed agricultural machinery

Aspect	Description	Application examples	Impact on design
Advantages			
Versatility	FEM can be applied to structures of any complexity, shape and geometry, including nonlinear elements, which allows modelling a variety of technical details	Modelling a trailer frame with complex geometry including welds and transition zones; analysis of gears in agricultural machinery	Allows designing equipment with non-standard shapes, providing accurate strength analysis
High accuracy	With a correctly constructed finite element mesh and a correctly specified model, FEM provides reliable results for predicting stresses and strains	Analysis of stresses in the hinge joints of a seeder under the action of dynamic loads from movement; assessment of the strength of the working elements of threshing machines	Increases the reliability of predictions, allowing avoiding excessive safety margins and optimising the design
Flexibility	The method allows taking into account various loading conditions (static, dynamic, vibration), as well as various material properties, including anisotropy and nonlinear behaviour	Modelling deformations of working parts of a fertiliser spreader with different materials under vibration loads	Provides the ability to adapt the design to different operating conditions and materials, increasing its efficiency
Automation and Integration with Computer-Aided Design (CAD)	FEM easily integrates with CAD systems, which allows automating the process of modelling, analysis and optimisation of structures, reducing design time	Importing a trailer model from a CAD system into FEM software for automatic stress analysis	Accelerates the design process, allowing quickly making changes and optimising the design
Fatigue analysis of materials and welds	FEM enables the evaluation of fatigue of materials and welds, which are critical for the durability of agricultural machinery	Fatigue life modelling of welds in trailer frames; fatigue analysis of gears	Increases the reliability of structures by allowing to identify potential failure zones and optimise critical elements
Potential for integration of advanced materials	FEM allows modelling the properties of composite materials and nanotechnologies that can improve the performance of equipment	Modelling of the working parts of the seeder using composite materials to reduce weight	Opens up opportunities for the use of innovative materials, increasing strength and energy efficiency
Limitation			
High computational costs	Complex models with numerous elements require significant computational resources and time, especially when analysing nonlinear problems or dynamic loads	Analysis of vibration loads on a trailer frame with a detailed mesh, which takes several hours of calculations	Limited analysis speed, required powerful equipment, increasing design costs
Sensitivity to sampling quality	FEM results depend on the quality of the finite element mesh and the correctness of the boundary conditions; errors in discretisation can lead to inaccurate results	Incorrect mesh in the trailer weld area leads to overestimated stresses in the model	Requires careful model preparation, potentially complicating the process for less experienced users.
The need for specialised resources	Effective FEM use required specialised software (e.g., ANSYS, Abaqus) and high user competence to set up tasks correctly	Using ANSYS to model the fatigue life of a drill requires knowledge of parameter settings	Increases costs for software and staff training, which can be a problem for small businesses
Limited consideration of real factors	FEM does not always take into account real operational factors, such as material wear, corrosion, or exposure to aggressive environments, which can affect the durability of the structure	The trailer frame model does not account for corrosion from wet soil, leading to an underestimation of wear	Reduces the accuracy of long-term forecasts, requires additional experimental studies for correction

Continued Table 2.

Aspect	Description	Application examples	Impact on design
Difficulties in fatigue analysis due to different approaches	Using different fatigue models (traditional vs. numerical) complicates analysis and can lead to conflicting results	Applying traditional fatigue models for a seed drill versus numerical models for a fertiliser spreader results in different durability predictions	Makes it difficult to standardise approaches, requires additional research to select the optimal fatigue model

Source: compiled by the authors based on X. Sun *et al.* (2023), J. Szusta *et al.* (2023), D.A.A. Esteban *et al.* (2024), S. Hussain *et al.* (2024), J. He *et al.* (2024), H. Raheman & P. Sarkar (2024), H.K. Celik *et al.* (2024), J. Neuhäusler *et al.* (2024)

FEM, despite the aforementioned limitations, remained one of the most powerful tools for structural analysis and optimisation in the technical design of towed agricultural machinery. Its application allowed for the achievement of key goals such as reducing structural weight, improving strength, and lowering maintenance costs – especially relevant in agriculture, where machinery was exposed to intensive loads and operated in harsh conditions. In Ukraine, particularly in the Mykolaiv region, where dense chernozem soils with high moisture levels and seasonal temperature fluctuations prevailed – such as elevated humidity in spring – FEM could be used to account for specific loads (increased soil friction and thermal deformations) in the design of towed agricultural machinery. This allowed for theoretical forecasting of structural performance and adaptation to local agricultural conditions, improving machinery efficiency and durability. FEM made it possible to optimise the construction of seeders and trailers by reducing trailer frame weight without losing strength or modifying the joints of seeders to enhance the resistance to vibrational loads under dense soil conditions, as shown in previous

studies (Celik *et al.*, 2024). The results of such theoretical developments could be applied at ESPC MNAU (Mykolaiv National Agrarian University, n.d.), which was engaged in practical agricultural research, including equipment, crop, and technology testing for further investigation and implementation in the Mykolaiv region.

Such measures contributed to achieving key goals – reducing structural weight, improving strength, increasing efficiency and durability, and lowering maintenance costs – which were particularly important in agriculture, where machinery experienced intense loads and operated in aggressive environments. To ensure maximum FEM effectiveness, it was recommended to combine numerical modelling with experimental research, which could be conducted at ESPC MNAU, thus enabling the consideration of real operating factors such as wear and corrosion and enhancing structural reliability. Table 3 systematised the key criteria for assessing the feasibility of applying FEM for structural optimisation. This structuring enabled the evaluation of advantages, limitations, and the importance of each aspect in designing specific structural components (e.g., seeder frames or fastening nodes).

Table 3. Comparative assessment of the capabilities of FEM in optimising the structures of agricultural machinery

Criterion	Parameter description	Advantages of FEM	Limitations/Risks	Significance for seeder structures
Calculation accuracy	The ability of the method to reflect the real distribution of stresses and strains in the structure	High accuracy provided that the mesh is of high quality and the boundary conditions are correctly set	Sensitivity to discretisation errors and inaccuracies in material parameters	Determinant for stress concentration zones, in particular fasteners
Flexibility for complex shapes	Ability to model complex geometry, the presence of holes, stiffeners, and changes in cross-sections	High: provides efficient modelling of structures of any complexity	Requires detailed mesh processing, which complicates calculations	Relevant for complex seed drill frame configurations
Computational costs	The number of resources and time required to create and solve the model	Allows optimising the design even at the design stage	Significant computational costs when numerous elements or taking into account nonlinearities	Balanced mesh detail is required to maintain performance
Integration with CAD/Computer-Aided Engineering (CAE)	Ability to interact with automated design and engineering analysis systems	Full compatibility with common CAD/CAE systems (SolidWorks, ANSYS, Abaqus)	Requires use of licensed software and qualified users	Facilitates accurate geometry transfer from design models
Consideration of variable loads	Ability to model dynamic, cyclic, shock effects typical of field conditions	Functionality is provided for analysing various load scenarios	Careful scripting and dynamic data input are required	Key to assessing resistance to real operational impacts
Fatigue/durability assessment	Predicting the service life of a structure under repeated loads	Ability to calculate fatigue life using appropriate modules (ANSYS, Abaqus)	Requires accurate data on materials and operating conditions	Critical for predicting the life of the drill in the field
Design optimisation	Automated geometry or topology changes to improve performance (mass, stiffness)	Topological, parametric and geometric optimisation are supported	Requires experience and methodological support for implementation	A decisive factor in reducing weight and production costs

Continued Table 3.

Criterion	Parameter description	Advantages of FEM	Limitations/Risks	Significance for seeder structures
Simulation of the real environment	Taking into account the influence of temperature, humidity, and soil abrasiveness on the structure	Possible if using multiphysics modelling (Multiphysics)	High requirements for calibration and input data availability, often not applicable in practice	Important for operating conditions in Ukraine (dense and wet soils)

Source: compiled by the authors based on H.K. Celik *et al.* (2024), J. He *et al.* (2024), B. Shan *et al.* (2024), S. Hussain *et al.* (2024)

The systematisation of criteria enabled a comprehensive assessment of the potential of FEM as an engineering analysis tool in the design of agricultural machinery. Key aspects included the method’s ability to identify stress concentration zones and accurately model complex structural geometries – which was critical for seeders operating in challenging environments. Of particular significance were the capabilities for analysing dynamic loads, fatigue strength, and integration with CAD/CAE, which substantially enhanced design cycle efficiency. Despite the complexity of modelling real soil and climatic factors, it was the multiphysics approach that opened up prospects for adapting machinery to regional conditions. FEM demonstrated high relevance for improving the reliability,

durability, and efficiency of structures in modern agricultural engineering. Structural optimisation was the process of improving the design and manufacture of technical systems to enhance the efficiency, reliability, and cost-effectiveness. It aimed to achieve the best structural parameters at minimal cost, taking into account all constraints, such as materials, resources, and operating conditions. Key aspects included minimising weight, improving strength, and reducing production and maintenance costs. For the optimisation of towed agricultural machinery structures, methods were applied that allowed a balance to be achieved between weight, strength, energy efficiency, and reliability. The description, application examples, advantages, and limitations are shown in Table 4.

Table 4. Main methods for optimising the designs of trailed agricultural machinery

Optimisation method	Description	Application examples	Advantages	Disadvantages
Topological optimisation	Finding the best structural design for given loads, material and geometry constraints, with the goal of reducing mass without sacrificing strength. Focuses on optimising shape for structures operating under high loads	Removing excess material in low-stress areas identified by FEM can reduce weight by 15%	Reducing the weight of the structure, reducing the energy consumption of the tractor, increasing the economic efficiency and energy efficiency of the machines	High computational requirements and complexity of model tuning, which may complicate practical application
Parametric optimisation	Adjustment of design parameters (wall thickness, element length) to achieve the optimal ratio between costs, strength and weight, adapting the machine to specific operating conditions	Adjusting the wall thickness of the planter support elements to adapt to variable loads on dense soils, which allows reducing material costs while maintaining strength	Adaptation of the structure to changing operating conditions (soil or climatic changes), reduction of material costs, increase of reliability	Less efficient under conditions of high variability of loads and physical parameters, which can limit the accuracy of optimisation
Geometric optimisation	Changing the structure’s geometry to improve performance – e.g., reduce vibrations, improve energy efficiency, and lower CO ₂ emissions, contributing to ecological sustainability	Modifying the shape of fertiliser spreader working elements to reduce vibration and improve energy efficiency, theoretically reducing CO ₂ emissions by up to 10% during operation	Reducing vibrations, increasing energy efficiency, reducing the environmental impact of equipment, improving aerodynamic properties to minimise fuel consumption	The need for precise measurements and complex design changes, which may not be economically feasible for a number of parts

Source: compiled by the authors based on J. Szusta *et al.* (2023), B. Shan *et al.* (2024), H.K. Celik *et al.* (2024), A. Soleimani *et al.* (2024), J. He *et al.* (2024)

Optimisation methods aimed to achieve a balance between key factors such as strength, weight, energy efficiency, and reliability of agricultural machinery structures, which were critical for the effective operation. The structural strength ensured the ability to withstand working loads and external impacts without damage, which was the basis for topological and parametric optimisation. The weight of a structure directly affected energy consumption – a heavier machine required more energy to move, while weight reduction achieved through topological optimisation could lower fuel consumption and increase

work efficiency. Energy efficiency was closely linked to geometrical optimisation, as improvements in geometry and material selection could reduce energy losses during operation and decrease CO₂ emissions. Structural reliability, achieved through parametric optimisation, defined the capacity to function for a long period without failures, which was essential for reducing maintenance costs and extending machine service life (Ivanovs *et al.*, 2018). These factors were interrelated and had to be optimised simultaneously to ensure durability, cost-effectiveness, and efficiency of agricultural machinery.

However, the methods also had drawbacks – discrepancies between theoretical models (built using FEM) and real operating conditions due to a focus on individual components and insufficient consideration of factors like material wear and corrosion. FEM's sensitivity to mesh quality and material parameters required careful tuning, and the high computational complexity, especially for complex structures, was a limitation. Ambiguity in material selection (lightweight materials in topological optimisation were less resistant to abrasive soil impact), and challenges in fatigue analysis due to differing approaches (traditional in parametric vs numerical in geometrical optimisation) were also present. These methods not only offered technical advantages but also impacted social, economic, and environmental aspects of using towed agricultural machinery, which was important for the sustainable development of the agricultural sector. In the social context, equipment modernisation through structural optimisation improved working conditions and operator safety. Reduction in vibrational loads on the frame of towed seeders through FEM lessened operator fatigue during long working cycles, enhancing labour productivity. Optimising energy processes on farms by improving equipment use promoted social stability, as reduced energy costs ensured more stable income for farmers (Jensen *et al.*, 2025).

The economic benefits of applying optimisation methods were also considerable. Implementing FEM for topological and parametric optimisation helped reduce structural weight and material costs, thereby lowering operational expenses. Precision agriculture, which relied on optimised equipment, reduced water and fertiliser use, and the integration of renewable energy sources, such as hydrogen, could reduce dependence on traditional fuels, improving the economic stability of farms (Ozguven, 2024; Anthony *et al.*, 2025). Optimisation methods had a positive environmental effect, contributing to reduced environmental pollution. Geometrical optimisation helped lower CO₂ emissions by improving machine energy efficiency, which, in turn, supported the positive impact of conservation tillage methods on reducing greenhouse gas emissions (Wang *et al.*, 2024). At the same time, these methods might contribute to N₂O emissions, requiring further study. The use of biogas and solar energy in agricultural systems incorporating optimised equipment reduced ecological pressure, supporting sustainability (Kiehadrouinezhad *et al.*, 2025).

In summary, integrating optimisation methods for the design of towed agricultural machinery ensured a balance between technical, social, economic, and environmental aspects, which should be key guidelines in developing new agri-technologies aimed at sustainable agri-sector development. The analysis of studies revealed key gaps in agricultural machinery design: insufficient use of modern composite materials and nanotechnologies, which could enhance strength, reduce weight, and improve energy efficiency of structures, and limited consideration of real operating conditions, such as variable weather and diverse soil types, due to the predominant focus on laboratory or

idealised models. The implementation of FEM in the design process of agricultural machinery had high potential to overcome these gaps and improve its efficiency. FEM enabled a significant increase in machine strength and reliability through detailed modelling of stress-strain states, thereby extending service life and reducing maintenance costs. Secondly, structural optimisation via FEM reduced production material costs and fuel consumption due to weight reduction and improved aerodynamics – potentially further enhanced by using composite materials and nanotechnologies. Thirdly, FEM enabled modelling of real operating condition impacts, such as climate changes, which ensured equipment resilience to weather challenges, including temperature fluctuations, droughts, or excess humidity.

This study analysed the potential for applying FEM in designing towed agricultural machinery, particularly seeders and trailers, and systematised knowledge about the influence of structural features and operating conditions on strength. The main findings confirmed the effectiveness of FEM in optimising structures by reducing weight, increasing strength, and lowering maintenance costs; revealed key research gaps, including insufficient use of composite materials and nanotechnologies; and limited accounting for real operational conditions such as variable weather and soil diversity. Reducing structural weight via FEM not only improved performance but also reduced fuel and maintenance costs, which was crucial for agricultural sector economic efficiency. In this context, these findings aligned with O.V. Dovgal *et al.* (2017), who emphasised that agri-enterprise competitiveness in Eastern Europe significantly depended on innovation. While that research focused on economic rather than technical design, technical innovations (such as FEM-based optimisation) could contribute to economic goals by boosting productivity and reducing costs. Likewise, the study by S. Ge & S. Zhao (2023) addressed agricultural machinery technologies and numerical modelling to assess performance and efficiency – closely matching the approach of the current study and confirming the importance of such methods.

The study identified a lack of attention to composite materials and nanotechnologies in agricultural machinery design, limiting potential for better technical characteristics like reduced weight and enhanced strength. M. Cutini *et al.* (2024) assessed official standards for evaluating the stability of self-propelled agricultural machines, especially narrow-track tractors. The theoretical calculations were based on idealised models, overlooking real field conditions like soil unevenness or weather variation. This supported current findings about limited consideration of real-world use. W. Lai *et al.* (2024) developed a Fibre Bragg Grating Sensor (FBG) to measure contact forces between grippers and vegetables during harvesting – yet the study was limited to lab tests, excluding real conditions (humidity, temperature, surface unevenness), which also aligned with current findings regarding focus on idealised models.

S. Li (2024) studied optimal parameter design of agricultural machinery using the ant colony algorithm to

enhance efficiency. This optimisation focus aligned with the current findings on seeder and trailer improvement. However, both studies lacked full consideration of real-world operating conditions, such as weather effects or soil diversity, which were vital for accurate analysis and optimisation. M. Cui *et al.* (2025) analysed volatile organic compound (IVOC) emissions from biodiesel-powered agricultural machinery under real operating conditions. The field measurements incorporated real usage, confirming the importance of studying such contexts. However, the authors did not factor in weather changes – partially aligned with this study's conclusions. To address this gap, additional modelling methods seemed promising. V. Shebanin *et al.* (2016) suggested fuzzy predicates and quantifiers in matrix representation for modelling information resources under uncertainty. Although the work did not focus on agri-machinery, such approaches had potential for modelling complex usage scenarios like climate variability – supporting the current study's view on the need for new methods accounting for real-world conditions.

The study confirmed that combining optimisation methods for the structures of towed agricultural machinery enabled harmony among technical, social, economic, and environmental factors. R. Alemanno *et al.* (2025) evaluated tractor performance and fuel use in vineyards, showing emission and cost reduction potential – directly aligned with the present research on agri-machinery optimisation. The focus on economic and ecological efficiency mirrored the study's emphasis on improving performance while reducing environmental impact. Similarly, E. Wallander *et al.* (2025), who studied electric farming with in-field energy replenishment, underscored sustainability and cost reduction – resonating with the environmental and economic themes of this work. M.R. Mesa *et al.* (2024) explored varieties of energy cane for biomass, highlighting economic and environmental benefits like new income sources and reduced fossil fuel dependence – matching this study's emphasis on sustainability and cost reduction. A. Elaoud *et al.* (2025) studied soil penetration resistance using Bayesian networks, considering parameters such as moisture and soil type that affected ecological resilience – the attention to soil diversity mirrored this study's findings. B. Wu *et al.* (2025) developed an all-terrain intelligent robot for harvesting, which reduced soil compaction and labour demands, while V.B. Shambhu *et al.* (2023) proposed a gender-orientated device for jute fibre extraction to improve women's working conditions. These studies' focus on social benefits of agricultural machinery echoed the current study's emphasis on easing and improving labour conditions.

Thus, applying composite materials in agri-machinery design, as this study showed, could reduce structural weight, boosting energy efficiency. Introducing electric tractors might reduce agri-machinery emissions – aligning with the study's ecological sustainability focus. Optimising structures using FEM could make machinery more accessible to small farms, improving productivity. ESPC MNAU, as a platform for practical research, could implement these

prospects by testing optimised designs in real operating conditions.

CONCLUSIONS

As a result of the study, the effectiveness of FEM for improving the design of towed agricultural machinery – in particular, seeders, and trailers – was established. FEM ensured a reduction in the weight of structures (up to 15% due to topological optimisation), an increase in the strength and resistance to vibrational impacts, as well as savings in operational costs through reduced material and fuel consumption. These changes contributed to economic benefits for the agricultural sector by lowering maintenance costs, environmental sustainability through reduced emissions (up to 10% due to geometric optimisation), and improved working conditions for operators by reducing vibrational loads, thereby enhancing productivity.

The analysis of existing approaches to agricultural machinery design revealed insufficient attention to the use of modern materials, such as composites and nanotechnologies, which hinders the achievement of better strength and lightness characteristics. It also showed an overreliance on simplified models that do not take into account variable climatic conditions and soil diversity. The study of structural features and operational conditions showed that towed machinery is subject to various loads, leading to material fatigue, corrosion processes, and local stresses – confirming the importance of numerical modelling for assessing these effects. The results are useful for the agricultural sector in regions with wet, dense soils, such as the Mykolaiv region. It is recommended to carry out equipment adaptation through numerical modelling, followed by testing of the improved designs at the ESPC MNAU base, with the aim of the practical implementation in real-world conditions.

The study had limitations related to its theoretical focus, which excluded experimental verification in field conditions, as well as insufficient attention to factors such as wear and corrosion, due to the emphasis on numerical modelling. The lack of available data on testing at ESPC MNAU made it difficult to assess the practical applicability of the results. In future, it would be advisable to focus on creating FEM models that take into account climatic and soil characteristics, conducting field experiments to validate theoretical developments, and studying the potential of composite materials and nanotechnologies for improving the strength, energy efficiency, and durability of the machinery. Such steps would improve the accuracy of forecasts and the practical relevance of developments for the sustainable development of the agricultural sector.

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Василь Грубань

Кандидат технічних наук, доцент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0003-0753-565X>

Антоніна Дробітько

Доктор сільськогосподарських наук, професор
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-6492-4558>

Микита Храмов

Асистент
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0000-0002-2537-7344>

Максим Товпига

Аспірант
Миколаївський національний аграрний університет
54008, вул. Георгія Гонгадзе, 9, м. Миколаїв, Україна
<https://orcid.org/0009-0009-5958-8359>

**Аналіз міцності та оптимізація конструкцій
причіпних сільськогосподарських машин
за допомогою методів кінцевих елементів**

Анотація. Мета дослідження полягала у вивченні потенціалу чисельного моделювання для вдосконалення аграрної техніки шляхом аналізу її характеристик і технологічних особливостей. Було виконано теоретичний аналіз із використанням теоретичного моделювання, що дозволило оцінити напружено-деформовані стани техніки під різними навантаженнями. Встановлено, що чисельне моделювання забезпечує зниження маси техніки шляхом видалення надлишкового матеріалу в зонах із низькими напруженнями, а також зменшення викидів завдяки вдосконаленню геометрії робочих органів, що сприяло економії енергії й підвищенню експлуатаційної ефективності. Виявлено, що сучасні технології недооцінюють потенціал композитних матеріалів і нанотехнологій, що обмежувало досягнення вищих показників міцності, легкості й довговічності, а спрощені моделі ігнорували змінні кліматичні фактори, різноманітність ґрунтів, вологість, температурні коливання, які впливали на знос і корозію техніки. Дослідження показало, що аграрна техніка зазнавала динамічних, циклічних, вібраційних і ударних впливів, які спричиняли втомне руйнування матеріалів і локальні напруження, особливо в зонах кріплення робочих елементів і шарнірних з'єднань, що знижувало термін служби і потребує вдосконалених матеріалів. Результати сприяли економічній вигоді аграрного сектору через зниження витрат на паливе й обслуговування, екологічній стійкості шляхом зменшення викидів, а також покращенню умов праці операторів завдяки зниженню вібраційних навантажень. Результати дослідження можуть бути використані при проектуванні та удосконаленні конструкцій причіпної сільськогосподарської техніки з урахуванням специфічних умов експлуатації, зокрема для попереднього моделювання й оптимізації робочих органів машин в аграрних регіонах із підвищеним навантаженням на раму

Ключові слова: чисельне моделювання; напружено-деформований стан; вібраційні навантаження; композитні матеріали; енергоефективність; реальні умови; аграрна техніка

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Anatolii Rud*

PhD in Technical Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
<https://orcid.org/0000-0002-7206-7103>

Anatolii Rud

PhD in Agronomy
Join Stock Company "Horodotske Pidpriemstvo "Agrohim"
32002, 2a Stantsiyna Str., Horodok, Ukraine
<https://orcid.org/0000-0002-1714-2596>

Development and implementation of electromechanical systems for the control of soil tillage units

Abstract. The need to improve soil cultivation technologies necessitates the introduction of electromechanical control systems that ensure energy efficiency, parameter stability, and increased effectiveness of mechanised agricultural processes. The purpose of this study was to design an intelligent control system capable of dynamically adapting operational modes based on sensor data and the principle of feedback. The research methodology included multi-level computer modelling in the MATLAB/Simulink environment, the development of a physical prototype using the STM32F407VG microcontroller, and experimental testing in laboratory and field conditions across plots with varying soil types. The system comprised modules for sensor monitoring of moisture, density, and load, a signal processing unit, a proportional-integral controller, and electric drives responsible for regulating tillage depth and force. The trials demonstrated the high stability of the system under variable agrophysical parameters, with a response time to external changes ranging from 1.8 to 2.3 seconds, and an average deviation in depth not exceeding five millimetres. The experimental results indicated a reduction in average energy consumption by 12-18% compared with conventional non-automated systems, and an increase in efficiency up to 87% on loamy soils. According to a multi-criteria performance analysis conducted using the Analytic Hierarchy Process, the electromechanical system achieved an integrated efficiency index of 4.37, significantly exceeding that of the hydraulic system, which scored 3.55. The practical implementation of the control system confirmed its technical suitability for mass integration into modern agricultural tillage machinery. The proposed technical solution improved the quality of soil cultivation, reduces energy consumption, minimises the need for operator intervention, and supports the sustainable development of the agro-industrial sector. The results of this study can be directly applied by agricultural enterprises in equipping soil tillage units with advanced electromechanical control systems, aimed at increasing precision, reducing fuel consumption, and improving machine productivity during field operations

Keywords: sensor monitoring; adaptive regulation; computer modelling; field testing; microcontroller; electric drive; digital interface

INTRODUCTION

The improvement of mechanised soil cultivation technologies is a key factor in enhancing the efficiency of modern agriculture. In the context of climate change, limited

energy resources, and the need for the sustainable use of land, the demand for the introduction of intelligent electromechanical systems is growing. These systems enable

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*Corresponding author



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greater precision in agrotechnical operations, reduce the mechanical impact on the soil, and lower energy consumption. The application of automated control allows real-time adaptation of tillage parameters to changing field conditions, ensuring the stability and quality of agrotechnological processes.

One of the priority areas involves the implementation of systems based on microelectromechanical components (MEMS), sensor devices, and adaptive control algorithms that integrate mechanical, electrical, and digital technologies. The study by I. Nazarenko & O. Kovalov (2021) focused on the creation and testing of an energy-efficient electromechanical system for tillage based on an electric tillage unit. The authors demonstrated that such a system reduces energy consumption, stabilises operating parameters, and enhances the quality of technological operations. Experimental field trials confirm the effectiveness of the proposed approach under real working conditions. Z. Guo *et al.* (2023) investigated the mechanical properties of the soil-tool interaction surface using entropy-weighted grey relational analysis. The authors developed a mathematical model enabling the precise determination of critical structural parameters influencing energy consumption during tillage. The results showed that optimising the geometry of the working surface significantly reduces resistance and increases the overall efficiency of the machinery.

V. Adamchuk *et al.* (2023) proposed an innovative mobile system for rapid, non-contact soil condition measurement directly during field operations. This solution involves the use of sensors capable of detecting soil density and moisture in real time, thereby avoiding the need to halt equipment during monitoring. This approach enhances the accuracy of technological operations and enables adaptive control of tillage parameters according to changes in the agrophysical characteristics of the environment. The relevance of precise sensor monitoring is further supported by the findings of K. Karyotis *et al.* (2021), who examined the potential for MEMS to assess the physicochemical properties of soil remotely without damaging its structure. Owing to their compact size and high sensitivity, MEMS sensors can be integrated into autonomous tillage complexes, providing continuous feedback between the cultivated environment and the control system. D. Tokarchuk & I. Furman (2021) conducted a comprehensive analysis of current energy-efficient technologies implemented within the agro-industrial sector of Ukraine. The study emphasised the importance of modernising tillage machinery, particularly through the introduction of electromechanical systems that contribute to reduced energy consumption and increased productivity. The authors also highlighted the necessity of regulatory frameworks and state support as essential conditions for the effective deployment of such innovations.

S.Y. Xu *et al.* (2024) focused on investigating the behaviour of the soil environment under loading conditions using digital image analysis methods. They examined the progressive destruction of soil structures occurring during

the operation of agricultural machinery, particularly in zones subject to intensive mechanical impact. The results obtained allow for the timely adaptation of tillage parameters to changes in the internal soil structure, reducing the risk of disrupting its integrity. K. Zeng & H. Liu (2023) investigated the temporal variation in the compressibility of calcareous sand under loading conditions that simulate the operation of tillage machinery. The paper demonstrated the mechanisms of compaction and shear, which are critical for determining the optimal pressure and movement speed of working tools in sandy soils. The findings contribute to improved accuracy in predicting soil behaviour and reducing the risk of machinery overload in unstable conditions.

N.-E. Yi & Y. Yang (2024) applied the discrete element method to model the wear of scrapers in gravel layers, which is crucial for optimising tool design. The authors identified critical wear points of working components, enabling improvements in materials and geometry to reduce wear under high mechanical loads. This study contributes to lower maintenance costs and extended equipment lifespan in challenging soil environments. M. Barzegar *et al.* (2022) reviewed the use of MEMS in geotechnical monitoring, particularly for measuring the physical and mechanical properties of soil in real time. Their study emphasised the importance of precise soil monitoring for the stable operation of machinery, as fluctuations in moisture and density can considerably affect technical performance. Owing to their compactness and high sensitivity, MEMS sensors provide continuous feedback between the soil and control systems, enabling real-time adjustment of operating modes (Suglobov *et al.*, 2024). These approaches gain particular relevance when combined with soil moisture sensing technologies based on electromechanical impedance. C. Lan *et al.* (2023) demonstrated this by developing spherical smart units for in-field monitoring. Their study showed that these devices can autonomously monitor soil moisture without the need to stop machinery, allowing for the optimisation of tillage machine operations. This approach facilitates the rapid adjustment of tillage parameters based on real-time data, increasing the efficiency and precision of fieldwork.

Modern research in agricultural mechanisation thus demonstrates the high potential of electromechanical solutions that integrate sensor systems, adaptive algorithms, and digital technologies. These developments open new possibilities for the creation of intelligent machinery capable not only of reducing operational costs but also of adapting to specific agrophysical conditions in real time. Such systems provide the foundation for high-performance, energy-efficient, and sustainable farming.

The purpose of this study is to conduct a comprehensive analysis of current electromechanical solutions for the control of soil cultivation machinery, to design and experimentally validate an adaptive control system based on sensor monitoring, and to evaluate its effectiveness and integration potential within agricultural engineering. Objectives of the study:

1. To analyse technical solutions in electromechanical control of soil cultivation units and identify their advantages and limitations.

2. To develop an adaptive control system using sensor modules and feedback algorithms.

3. To conduct laboratory and field trials of the developed system and assess its performance based on control accuracy, energy consumption, and adaptability to agro-physical conditions.

MATERIALS AND METHODS

At the first stage of the study, a theoretical analysis of existing electromechanical control systems used in contemporary agricultural machinery engineering was conducted. The analysis considered the structural features of soil cultivation mechanisms, types of drives, components of working tool actuators, and the integration of sensor and actuator devices into implement architecture. Particular attention was given to the comparison between conventional hydromechanical systems and electromechanical assemblies based on microprocessor control. A literature review was conducted regarding parameters such as stability, precision, energy consumption, and wear resistance of electromechanical control systems under various operating conditions, including the use of electric motor blocks for energy-efficient tillage (Nazarenko & Kovalov, 2021), the analysis of mechanical properties of working tools through the entropy-weighted grey relational method (Guo *et al.*, 2023), the development of tools for rapid measurement of soil condition indicators (Adamchuk *et al.*, 2023), and the evaluation of MEMS-based sensors for agricultural monitoring (Karyotis *et al.*, 2021).

The second stage of the study involved modelling the kinematics and dynamics of the soil cultivation implement, considering variable agro-physical parameters of the environment, namely, soil density, moisture, and resistance. The modelling was conducted using the MATLAB/Simulink computing environment. A structural system model was built, comprising sensor components (load, moisture, and position sensors), a data processing unit (STM32F407VG microcontroller), and control algorithms. During simulation, the operational ranges of parameters, critical loads, and feedback delays were determined. The data obtained formed the basis for the development of adaptive regulation algorithms for the implement's working modes.

The third stage involved the development of a physical prototype of the electromechanical control system. The prototype included: an STM32F407VG microcontroller (manufactured by STMicroelectronics, France/Italy), based on the ARM Cortex-M4 architecture, with a clock speed of up to 168 MHz, equipped with 1 MB of flash memory, 192 KB of RAM, three 12-bit analogue-to-digital converters, 17 timers, up to 114 GPIO lines, and a wide set of interfaces (USB OTG, SPI, I2C, USART, CAN), providing stable operation of the sensor and actuator modules under variable agro-physical conditions; sensor units incorporating both digital and analogue moisture, temperature, density, and

soil resistance sensors, with real-time data output via the controller; vector-controlled electric drives capable of regulating force, penetration depth, and movement speed of the working tools depending on sensor input; and a digital operator interface based on a touch-screen display with CAN communication protocol, enabling the operator to set working parameters, monitor performance in the field, and remotely adjust the system's functional modes. The system was tested under laboratory conditions using a test bench designed to simulate dynamic loads and variable soil structures. During testing, parameters such as positioning accuracy, response time, control stability, and overall energy consumption were monitored.

The fourth stage involved testing the developed electromechanical system in agricultural fields with various soil types, including loam, sandy-clay, and waterlogged soils. A series of measurements were performed under varying conditions of moisture, resistance, and surface relief. Using built-in sensors and an autonomous data logger, measurements were taken of the loads on the working tools, the quality of soil treatment, the stability of preset parameters, and the energy use coefficient. The results were compared with equivalent data from standard (non-controlled) systems, enabling an objective assessment of performance gains. Field testing of the electromechanical control system was conducted at three sites with contrasting agro-physical properties: loamy, sandy-clay, and waterlogged soils. The aim of the testing was to evaluate system stability under real operating conditions, particularly its response to changes in soil moisture, resistance, surface topography, and mechanical load. Particular attention was given to measuring parameters such as depth control accuracy, the level of adaptation of the system to changing environmental characteristics, and energy efficiency, which was assessed based on the coefficient of performance.

The final stage involved a comparative analysis of the electromechanical system against other control methods, based on criteria including energy efficiency, regulation accuracy, economic feasibility, and operational reliability. The analysis was conducted using the Analytic Hierarchy Process (AHP) method, supported by data from experimental measurements. For implementation of the AHP method, the Saaty nine-point scale was used, with pairwise comparisons of criteria and alternatives. According to this scale, a score of 1 indicates equal importance, 3 indicates moderate preference of one element over another, 5 indicates strong preference, 7 indicates very strong preference, and 9 indicates absolute dominance. Scores of 2, 4, 6, and 8 were used as intermediate values to refine the intensity of preference. Expert evaluations were aggregated into a pairwise comparison matrix, from which weighting coefficients were calculated to reflect the priority of each criterion. This allowed ranking the technical solutions according to a composite efficiency indicator and justifying the selection of the optimal system modification for mass production. The results were summarised in tables and graphs, which

substantiated the feasibility of integrating the developed system into serial models of agricultural machinery.

RESULTS

Analysis of functional capabilities of electromechanical systems in modern soil cultivation machinery

Modern agricultural machinery is undergoing intensive modernisation driven by the need to improve energy efficiency, precision, and operational stability under variable agrophysical conditions. One of the most promising areas for technical renewal involves the introduction of electromechanical control systems, which are gradually replacing conventional hydromechanical and mechanical solutions. A defining feature of electromechanical systems is their ability to deliver high-precision regulation of technological parameters – cultivation depth, applied force, travel speed, etc. – in real time through microprocessor control and integrated sensor systems. Such systems employ stepper or brushless electric motors, which offer compact dimensions, low noise, high reliability, and precise positioning. In

addition, the electric drives can operate in a closed cycle with constant correction of the output signal in accordance with the data coming from the sensors. This capability proves critical when operating on fields with complex structure or heterogeneous soil properties, where maintenance of stable parameters without loss of processing quality is essential.

Conventional hydraulic systems, although capable of delivering significant tractive effort, are inferior to electromechanical systems in terms of precision, sensitivity to external influences, and energy consumption (Panchenko *et al.*, 2018). For instance, energy losses in a hydraulic circuit may reach 25-30% owing to fluid heating and pressure drops in piping. Hydraulic systems also require regular maintenance, fluid changes, and filter replacements, which increases overall operating costs (Bulgakov *et al.*, 2020). A comparative characterisation of the three main types of control systems – mechanical, hydraulic, and electromechanical – is presented in Table 1, based on indicators such as regulation precision, energy consumption, dynamic stability, reliability, maintainability, and adaptability.

Table 1. Comparative characteristics of control systems

Indicator	Mechanical system	Hydraulic system	Electromechanical system
Regulation accuracy	Low	Medium	High
Energy consumption	Medium	High	Low
Dynamic stability	Low	Medium	High
Reliability	High	Medium	High
Maintainability	High	Medium	Medium
Adaptability	Low	Medium	High

Source: created by the authors based on Z. Guo *et al.* (2023), V. Adamchuk *et al.* (2023)

As shown in Table 1, mechanical systems, despite high maintainability and reliability, are inferior to contemporary solutions in regulation precision and adaptability to variable operating conditions. Hydraulic systems demonstrate better performance than mechanical systems in terms of precision and dynamic stability, yet they suffer from increased energy consumption and only medium maintainability owing to complex maintenance requirements and frequent fluid replacement (Voloshina *et al.*, 2021). Electromechanical systems, by contrast, received the highest ratings for precision, dynamic stability, and adaptability. This

is due to intelligent control algorithms, integration with sensor hardware, and real-time feedback. Energy consumption is reduced through optimisation of operating modes and the elimination of hydraulic resistance losses or mechanical friction (Havrylenko *et al.*, 2021). Despite medium maintainability, which reflects the need for specialised technical servicing, the overall balance of advantages makes the electromechanical system the most suitable choice for intensive, high-precision agricultural production. Figure 1 presents the functional schematic of sensor and actuator integration within a soil cultivation implement.

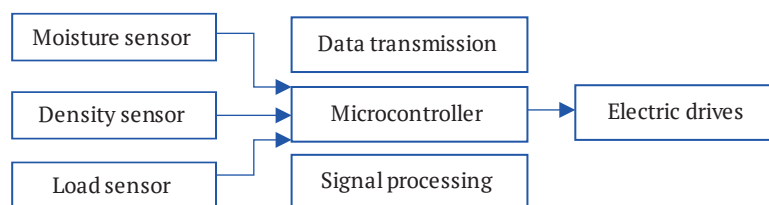


Figure 1. Functional schematic of sensor and actuator integration within a soil cultivation implement

Source: compiled by the authors

The schematic in Figure 1 details the logic of an automated electromechanical control system for a soil cultivation implements, based on closed-loop feedback. In the first stage, specialised sensors continuously measure agro-

physical parameters: a moisture sensor records soil moisture, which influences optimal working depth; a density sensor evaluates soil structure and compaction, allowing adaptation of implement operation to changes in resist-

ance; and a load sensor monitors mechanical force applied to the working element, signalling potential overload or unstable operation. Sensor data are transmitted in real time to the microcontroller, which serves as the central control unit (Bazilo *et al.*, 2023). Initial signal processing involves conversion of analogue values to digital form, noise filtering, normalisation, and preliminary parameter analysis (Hula & Hryha, 2024). Next, the signal-processing block executes adaptive control algorithms that compare current system status with reference values and generate commands for actuators. The actuator block comprises electric drives capable of adjusting working depth, travel speed and applied force according to control signals. These drives provide high positioning accuracy, maintaining set parameters with minimal deviation even when soil properties or field topography change abruptly. A key feature of this system is the closed-loop feedback cycle: after executing a command, actuators return updated state data to the sensor sub-system, enabling rapid correction cycles. This architecture ensures immediate response to changing conditions, such as transitions from compacted to loose soil or the encounter of mechanical obstacles. As a result, the system maintains high operational stability

even when cultivating challenging zones, uneven terrain or areas with varying moisture and density, thereby remarkably improving the quality and energy efficiency of agrotechnical operations.

Results of computer modelling and control algorithm testing

At this stage of the study, computer modelling of the electromechanical control system for the working elements of a soil cultivation implement was conducted using MATLAB/Simulink. The primary objectives of the modelling were to reproduce system responses to changes in agrophysical parameters, namely density, moisture, soil resistance, to verify feedback algorithms and determine time delays and stability limits of electric drives under variable load conditions.

In the Simulink environment, a structural model was developed, comprising the following subsystems: an input disturbance generator block, simulating variations in soil physical parameters; sensor blocks; a signal processing module; PI controllers; and a model of the electric drive with load. Figure 2 illustrates the overall logic of the model, which implements an adaptive control scheme accounting for sensor reaction delays and drive inertia.

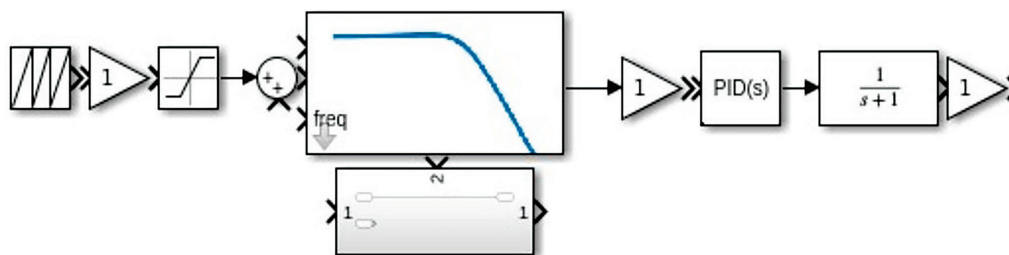


Figure 2. Structural diagram of the adaptive control system model for the electric drive of a soil cultivation implements in Simulink

Source: compiled by the authors

As shown in Figure 2, the scheme simulates a full operational cycle under variable agrophysical conditions – soil resistance, moisture, and density – considering drive dynamics, sensor reaction characteristics, and control algorithms. Visually, the model appears as a closed-loop feedback circuit with distinct blocks for disturbance generation, sensor monitoring, signal processing, PI control, actuator dynamics, and system output response. The model employs an input signal generator block to simulate time-varying soil resistance. A Repeating Sequence block provides periodic disturbances, enabling the definition of a time-dependent physical load on the implement. This signal is then scaled and normalised by a Gain block to match typical sensor measurement ranges. A Saturation block follows, representing the limited range of real sensors, which cannot record values outside specified bounds. After initial signal conditioning, the processed signal enters a comparison logic, where it is contrasted with a reference value – representing an optimally defined depth or force of cultivation. An error-generation mechanism in the

computational core produces an error signal, which is passed to the signal-processing block. Here, smoothing is performed by a Lowpass Filter block, simulating the inertial nature of sensor measurements and filtering out transient pulse changes or background noise.

Once the signal is stabilised, the information feeds into the PI controller block, implemented using a standard PID Controller with the derivative component disabled. The control algorithm ensures a gradual system response to increases or decreases in deviation from the reference. During modelling, proportional and integral gains were tuned to achieve minimal transient time, prevent overshoot, and eliminate oscillations in response to sudden disturbances. The final block of the model simulated the response of the electric drive to a given command. For this purpose, the transfer function $1/(s+1)$ is used, which captures the inertia of the system, that is, the actual delay between the control input and the operation execution. This feature holds particular importance in an agrotechnical environment, where rapid response to changes in

soil resistance is critical for maintaining implement stability. The model concluded with feedback that routes actual performance data back into the control system. In this way, a closed loop is formed, in which every parameter change is immediately captured, processed, and used to generate a revised control signal. The resulting structure permits investigation of system responses to

variations in any single parameter, tuning of stabilisation algorithms, and assessment of their effectiveness under simulated field conditions. Several scenarios were modelled, ranging from a sudden increase in soil resistance to a gradual decrease in moisture. In each case, the dynamic response of the electric drives was recorded and is presented in Figure 3.

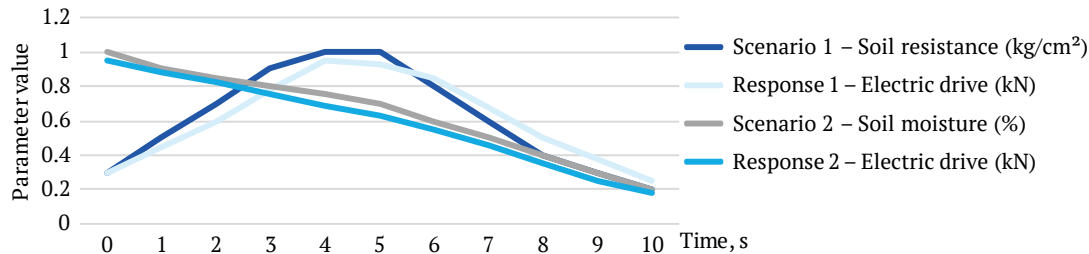


Figure 3. Simulation of electric drive response

Source: compiled by the authors

Figure 3 illustrates the simulated response of the electric drive to changes in agrophysical soil parameters under two representative scenarios: a rapid rise in soil resistance and a gradual reduction in soil moisture. The first scenario, reflected by the curve “Scenario 1 – Soil resistance (kg/cm^2)”, simulated the implement traversing successive field sections of increasing mechanical resistance. The initial resistance measured $0.3 \text{ kg}/\text{cm}^2$ and rose to $1 \text{ kg}/\text{cm}^2$ over the first four seconds. Once the peak was reached, resistance declined gradually to $0.2 \text{ kg}/\text{cm}^2$, simulating exit from a compacted zone. Corresponding to this profile, the electric drive output force rose from 0.3 kN to 0.95 kN (curve “Response 1 – Electric drive (kN)”), before smoothly reducing to 0.25 kN . Such behaviour demonstrates the presence of an adaptive mechanism that stabilises load under changing external conditions. The second scenario analysed a reduction in soil moisture from 1% to 0.2% over ten seconds. The drive output force fell from 0.95 kN to 0.18 kN , indicating correct operation of inertia-compensation algorithms and effective integration of

sensor data into the control scheme, which adjusts actuator commands according to the current environmental state. Curve analysis shows that both drive responses combine rapidity with controllability. Parameter changes follow a smooth profile with adequate regulation speed, rather than occurring abruptly. Calculated transition times, the interval required for full adaptation to a disturbance, range on average from 1.8 s to 2.3 s , a sufficiently fast response for practical field operation.

Maximum deviations of the drive response curve did not exceed $8\text{--}10\%$ of the set values, reflecting high regulation accuracy and consistency. This outcome confirms the effectiveness of the implemented PI control algorithms, which deliver stable performance despite variable agrophysical conditions. Figure 3 thus clearly demonstrates that the developed control approach can adapt flexibly, while the electric drive executes control actions precisely without significant loss of time or energy. Table 2 presents the consolidated characteristics of stability and response speed under simulated agrophysical variations.

Table 2. Characteristics of stability and response speed

Type of scenario	Average regulation time, s	Maximum overshoot, %	Damping coefficient	Stability rating
Gradual increase in resistance	1.8	6	0.85	High
Impulse disturbance of resistance	2.3	10	0.65	Medium
Gradual reduction in moisture	2	7	0.8	High
Impulse reduction in moisture	2.4	11	0.6	Medium

Source: compiled by the authors

As shown in Table 2, the system response to simulated agrophysical changes depends strongly on the external disturbance. In the gradual increase in soil resistance scenario, the control scheme delivered the highest stability metrics: an average regulation time of 1.8 s , a maximum

overshoot of only 6% , and a damping coefficient of 0.85 , indicative of effective smoothing without excessive inertia. A similarly high stability level emerged in the gradual moisture-reduction scenario, with an average regulation time of 2.0 s and a damping coefficient of 0.8 .

By contrast, under impulse disturbances of resistance or sudden moisture reduction, stability decreased: regulation time increased to 2.3-2.4 s, damping coefficient fell to 0.6-0.65, and maximum overshoot reached 10-11%. These results highlight greater sensitivity of the control scheme to abrupt changes and underscore the need for precise tuning of PI controllers.

Overall, the table data confirm the effectiveness of the adaptive control scheme under gradual changes in soil parameters. The results highlight the importance of tuning regulator settings in the event of impulse disturbances, which minimises excessive overshoot and preserves energy efficiency. High damping coefficients in stable scenarios indicate minimal energy expenditure on corrective oscillations, a key efficiency metric in real-world field operation. Special attention was paid to assessing resilience when sensor data are limited. Simulation of signal loss from one or more sensors showed that, despite reduced input, the control approach maintains acceptable performance using a predictive model based on trends in previous measurements. In addition, an algorithm for early detection of critical conditions – such as drive overload or implement jamming – was tested. The control scheme autonomously reduced drive load or issued a stop alert to the operator interface. Taken together, the computer modelling results confirm that the proposed control scheme delivers high adaptability, satisfactory response speed, and robustness against typical field disturbances.

Laboratory testing of the electromechanical control prototype

At this stage, experimental testing of the physical control prototype was conducted under laboratory conditions designed to replicate real-world field scenarios as closely as possible. The primary aim of these tests was to determine key dynamic parameters: response time, working-element positioning accuracy, depth stability, and energy consumption across various operating modes. Laboratory trials were performed on a variable-load test rig that simulated changes in agrophysical conditions. The prototype was connected to an STM32F407VG controller, which managed the actuators via adaptive PI regulation algorithms. The controlled parameter was working-element immersion depth in a soil-like medium, measured by an integrated position sensor with 0.1 mm resolution. Data were recorded at 100 Hz by an autonomous logger, enabling detailed temporal analysis.

Under baseline load (up to 50% of nominal), the average response time after a control command was 1.5-1.7 seconds. When load increased to 80-90%, response time rose to 2.2 seconds, yet the control approach remained within acceptable accuracy limits. Maximum deviation from the target depth did not exceed ± 3 mm under background vibrations and disturbances. These indicators confirm the high effectiveness of the feedback scheme in ensuring rapid and smooth positioning. Energy consumption was analysed for each operating mode. The results are shown in Figure 4, which depicts power draw in watts at various load levels.

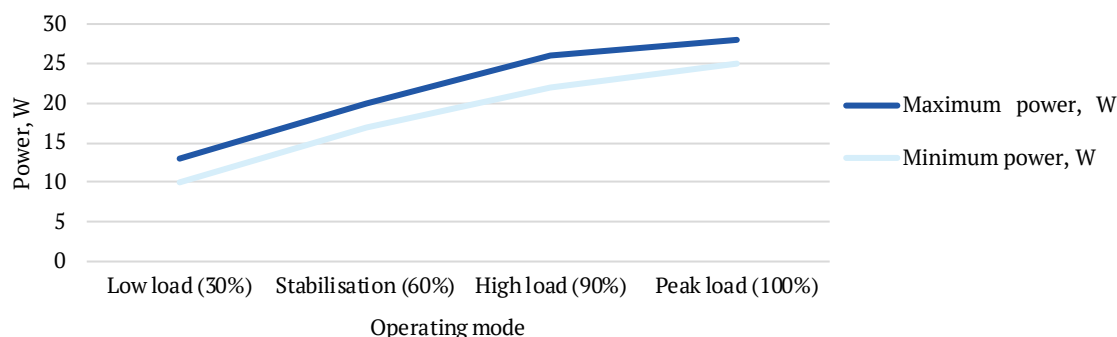


Figure 4. Relationship between power consumption and load regime in the electromechanical control scheme

Source: compiled by the authors

As shown in Figure 4, the power consumption of the electromechanical control approach is directly dependent on operating mode and load level. The graph illustrates the variation in minimum and maximum power draw under four distinct regimes, ranging from low load (30% of nominal) to peak load (100%). In the standard stabilisation mode (60%), which corresponds to typical field operation, the scheme exhibits consumption in the range of 17-20 W, confirming its energy efficiency under controlled conditions. At high load (90%), power consumption rises to 22-26 W, which remains within the acceptable threshold for the selected drive configuration. Peak power consumption, recorded at full load (100%), reaches 28 W. However, even under this condition, the control approach operates

without overload. A particularly notable outcome is the avoidance of power spikes, which typically occur in systems with fixed or non-adaptive control logic. This was achieved through automated control with real-time force adjustment. All regimes demonstrate a relatively stable amplitude between minimum and maximum consumption, indicating reliable load compensation and the effectiveness of the control logic. Overall, Figure 4 confirms that the proposed scheme is capable of maintaining optimal energy performance across a wide range of loads, rendering it suitable for deployment in energy-sensitive soil cultivation processes. Summary results are provided in Table 3, which compares stabilisation and power parameters across three primary load levels – low, medium, and high.

Table 3. Depth stabilisation and power consumption parameters

Load level	Mean depth deviation (mm)	Stabilisation time (s)	Average power (W)	Maximum power (W)
Low (30%)	4.2	2.4	11	13
Medium (60%)	2.1	1.8	18.5	20
High (90%)	3.5	2.3	24	26

Source: compiled by the authors

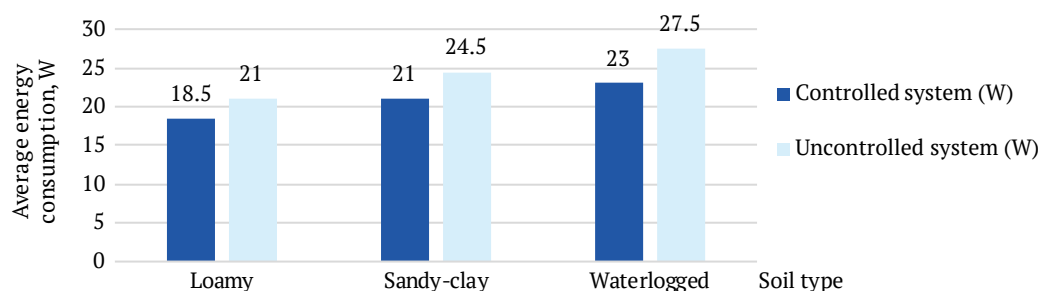
As shown in Table 3, the dynamic parameters of the stabilisation scheme vary considerably depending on the applied load level. Analysis of the presented data supports the conclusion that an optimal balance between positioning accuracy, stabilisation time, and power consumption is achieved at medium load, approximately 60% of nominal capacity. Under this regime, the mean deviation in depth is just 2.1 mm, the lowest among all three tested levels. Stabilisation time is also shortest at 1.8 seconds, and power consumption remains between 18.5 and 20 W, confirming efficient operation without excessive resource use. In comparison, low load conditions result in higher deviation, reaching 4.2 mm, along with lower energy use. However, this is accompanied by a noticeable increase in stabilisation time, rising to 2.4 seconds. This may be attributed to insufficient force to quickly adjust the depth when working pressure on the implements is minimal. At high load (90%), stabilisation accuracy decreases slightly to 3.5 mm, and average power rises to 24 W, indicating greater strain on the drive unit. Although these values remain within acceptable limits, system efficiency under this regime is lower than at medium load. In summary, Table 3 confirms the viability of adaptive control logic, which enables the drive force to be automatically adjusted according to current operating conditions. This approach ensures not only stable operation of the implement but also energy efficiency, which is a key requirement for the integration of contemporary electromechanical solutions in soil cultivation machinery. Laboratory testing confirmed that the developed electromechanical control approach is capable of responding to changes in external conditions with precision and consistency. Its

advantages lie in the combination of rapid response, minimal energy consumption, and high positioning accuracy, which qualifies it as an effective alternative to conventional control configurations in soil treatment equipment.

Results of field trials across different soil types

Overall, the approach demonstrated stable performance across all soil types, with variation in output indicators attributable to the physical properties of the surface. On the loamy section, the highest depth stabilisation accuracy was observed, with a mean deviation not exceeding ± 2.8 mm, indicating strong adhesion to the working environment and stable contact force. In the sandy-clay layer, irregular density caused more frequent, short-term deviations within ± 4.1 mm, although the approach quickly returned to the target depth. The greatest load on the drive unit and the longest response delay were recorded on waterlogged areas, where the saturated layer generated variable resistance, leading to deviations of up to ± 5 mm and a slightly reduced stabilisation coefficient.

Analysis of adaptability confirmed the capacity of the system to respond rapidly to changes in soil moisture. Under a sudden increase in moisture content above 30 per cent, the drive unit adjusted its force within the range of 0.4–0.6 kN without overloading or compromising accuracy. The efficiency coefficient (calculated as the ratio of actual force output to energy expenditure during the stabilisation cycle) averaged 87% on loamy soil, 83% on sandy-clay soil, and 79% on waterlogged terrain. Figure 5 shows a comparison of the energy consumption of an electromechanical controlled system with a conventional uncontrolled system.

**Figure 5.** Comparison of energy consumption between controlled and uncontrolled systems

Source: compiled by the authors

Figure 5 provides a visual comparison of the mean energy consumption of the electromechanical controlled approach and a conventional uncontrolled configuration across three soil types: loamy, sandy-clay, and waterlogged. The diagram offers a clear evaluation of the

adaptive control method's efficiency in comparison with standard technological arrangements, which lack active feedback and drive mode variability. According to the data in Figure 5, mean energy consumption on loamy soils for the controlled approach was 18.5 W, whereas the

uncontrolled configuration required 21 W, resulting in a 2.5 W saving, or approximately 12%. The greatest benefit was recorded on sandy-clay terrain, where the adaptive approach consumed 21 W, compared to 24.5 W for the conventional one, exceeding a 14% difference. On waterlogged soil, considered the most challenging due to high saturation and unstable structure, the advantage of the controlled approach was even more pronounced: 23 W versus 27.5 W, indicating a reduction in energy expenditure of over 16%. The overall trend illustrated in Figure 5 confirms that the implementation of an adaptive control

algorithm substantially reduces energy consumption. This is due to two main factors. First, it reduces excessive drive force during stabilisation, avoiding the overcompensation characteristic of fixed logic configurations. Second, real-time optimisation of drive operation enables dynamic adjustment of force parameters according to the current mechanical resistance of the soil, reducing losses from idle operation and unnecessary overloading. The aggregated data concerning treatment quality are presented in Table 4, which summarises indicators of depth accuracy, positioning stability, and energy efficiency.

Table 4. Indicators of treatment quality across different sections

Soil type	Mean depth deviation (mm)	Positioning stability (score 1-5)	Efficiency coefficient (%)	Need for manual correction
Loamy	2.8	5	87	None
Sandy-clay	4.1	4	83	Minimal
Waterlogged	5	4	79	Minimal

Source: compiled by the authors

As shown in Table 4, the approach demonstrates high-quality performance across various soil types. The best results were recorded on loamy soil, where the mean deviation in depth was only 2.8 mm, positioning stability received the maximum score of 5, and the efficiency coefficient reached 87%, with no need for manual intervention. On sandy-clay and waterlogged soils, precision declined slightly (to 4.1 mm and 5.0 mm respectively), although stability remained high (scored at 4), and efficiency remained adequate (83% and 79% respectively). In all scenarios, the approach functioned autonomously, with minimal or no requirement for manual adjustment, confirming its practical reliability and adaptability to variable field conditions.

Comparative evaluation of control system efficiency

In order to substantiate the feasibility of implementing the electromechanical control system, an Analytical Hierarchy Process (AHP analysis) was conducted with the objective of multi-criteria comparison of the efficiency of different

control systems, specifically the electromechanical and hydraulic types. The AHP methodology enabled the construction of a decision-making framework with a clear hierarchy of priorities, within which four main criteria were considered: regulation accuracy, energy efficiency, adaptability to changing external conditions, and operational reliability.

The weighting coefficients of each criterion were determined through pairwise comparison, based on expert surveys involving specialists in agroengineering and automation. The highest weight was assigned to energy efficiency (0.35), followed by regulation accuracy (0.3), adaptability (0.2), and reliability (0.15). This distribution reflects the current relevance of reducing energy consumption, which plays a decisive role in the cost-effectiveness of engineering solutions under present conditions of elevated energy prices. Table 5 presents the assessment of the electromechanical and hydraulic control systems according to all criteria, based on a five-point scale, with the subsequent calculation of the integral efficiency index according to the weighted average formula.

Table 5. Assessment of control systems according to AHP method

Criterion	Weighting coefficient	Electromechanical control system (points)	Hydraulic control system (points)
Regulation accuracy	0.3	4.5	3.8
Energy efficiency	0.35	4.7	3.5
Adaptability	0.2	4.4	3.2
Operational reliability	0.15	3.8	4.5
Integral index	-	4.37	3.55

Source: compiled by the authors

As shown in Table 5, the results of the AHP analysis indicate that the electromechanical control system receives higher scores in three out of the four key criteria: regulation accuracy (4.5 versus 3.8), energy efficiency (4.7 versus 3.5), and adaptability (4.4 versus 3.2). The hydraulic system scores higher in reliability (4.5 versus 3.8), although this

advantage is insufficient to offset the overall difference. The aggregated integral efficiency index was calculated at 4.37 for the electromechanical system and 3.55 for the hydraulic one, indicating the superiority of the former under multi-factor analysis, and confirming its relevance for integration into modern agrotechnologies.

Figure 6 visualises these integral indicators, clearly illustrating the dominance of the electromechanical control system across all priority criteria except for reliability, where hydraulics still retains a relative advantage due to their simple and well-established construction. Nevertheless, due to sustained reductions in power consumption, higher regulation accuracy, and the ability to adapt to changing conditions, the electromechanical system outperforms its alternative in the overall assessment. Figure 6 presents the aggregated results of the AHP analysis in the form of a comparative diagram between the electromechanical and hydraulic control systems according to key efficiency criteria. Evidently, the electromechanical system outperforms in regulation accuracy (4.5 points), energy efficiency (4.7 points), and

adaptability (4.4 points). In contrast, the hydraulic system leads only in the criterion of reliability (4.5 points), which is attributed to its simplified design and lower sensitivity to external disturbances. The overall integral efficiency index amounts to 4.37 for the electromechanical system, compared with 3.55 for the hydraulic one, which visibly confirms the feasibility of implementing adaptive electromechanical control in modern soil cultivation machinery. The diagram also reflects the balance across all criteria, enabling transparent tracking of the decision-making logic based on objective, multi-factor assessment. Accordingly, Figure 6 serves as an illustrative synthesis for technical and economic decision-making, in which preference is given to an innovative system with a high potential for adaptation.

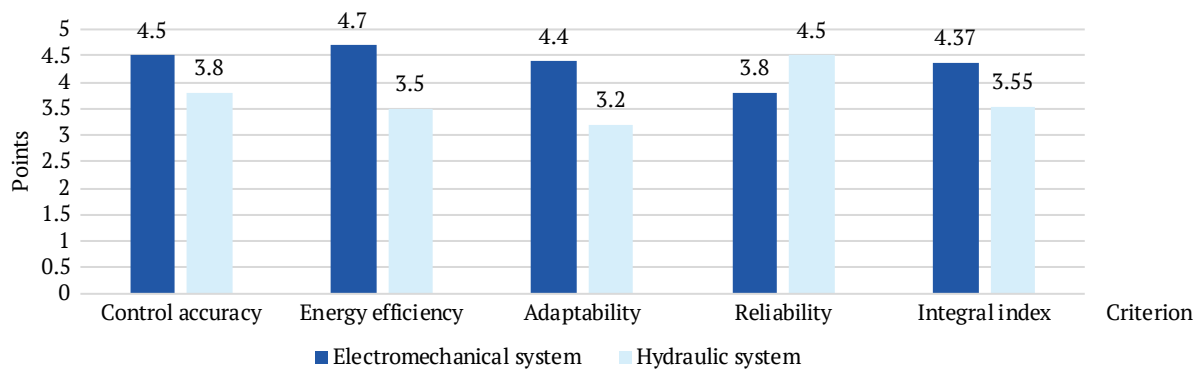


Figure 6. Integral indicators of control system efficiency

Source: compiled by the authors

As a result of completing the full research cycle – from theoretical justification to simulation, laboratory testing, and field trials – a comprehensive understanding of the efficiency of the proposed electromechanical control system for soil cultivation units was achieved. At every stage, the system demonstrated consistent performance in terms of accuracy, energy efficiency, and adaptability, which substantiates its practical suitability for large-scale implementation in the Ukrainian agro-industrial sector.

DISCUSSION

This study confirms the effectiveness of the electromechanical control system in agricultural machinery, particularly under dynamically changing agrophysical conditions. High levels of regulation accuracy, disturbance adaptability, and energy consumption stability demonstrate the practical relevance of the proposed solution for integration into soil cultivation equipment. These findings align with those of C. Gu *et al.* (2024), who evaluated the applicability of a two-dimensional piezoelectric transducer for dynamic load monitoring in uncompacted soil layers. The authors emphasised the necessity of precise detection of changes in the physical state of the medium to ensure effective actuator performance, a requirement mirrored in the present approach, where the sensor system plays a central role in feedback development. M.K. Manalu *et*

al. (2025) highlighted the importance of accurate collection and processing of dynamic data for adapting electromechanical system parameters. Their study presented a novel seismic data acquisition system used to measure particle velocity and distance to the vibration source. Although their field of application differs (geophysics), the principle of precise dynamic monitoring and real-time data processing parallels the microcontroller-driven analysis of agrophysical parameters employed in this study. H. Liu *et al.* (2024) investigated an adaptive temperature control technology built on multiphysical modelling that integrates thermal, hydraulic, and mechanical interactions. Their methodology automatically adjusts tunnel lining structure in response to environmental temperature changes; similarly, the system developed in this study implements adaptive regulation of soil resistance, moisture, and density, ensuring effective response under complex field scenarios. R. Raafi *et al.* (2025) analysed a new design of electromagnetic machines featuring π -shaped stator elements to reduce electromagnetic friction losses. Their approach, as in the one presented here, achieves system effectiveness through engineering refinement of the actuator design. Both studies demonstrate that regulation accuracy and energy savings are achieved not only through algorithmic control but also through optimisation of hardware architecture.

D.K. Woo *et al.* (2022) proposed a novel non-invasive method for assessing soil moisture using ultrasonic technology, which does not require mechanical contact with the medium. The approach delivered high measurement accuracy without disturbing soil structure, a feature particularly important when working with heterogeneous or wet soils. In the present study, although conventional sensors were used, a similar effect was achieved by increasing sampling frequency and deploying fluctuation-correction algorithms, which stabilised actuator response under dynamic moisture changes. A. Khatibi *et al.* (2022) investigated a hybrid control system for electrochromic smart windows, employing combined adaptation and compensation methods for varying external parameters. They discovered that multicomponent control provided superior energy efficiency and stability. These results correspond with the present study, which demonstrated PI controller effectiveness in simulated scenarios, where the system responded without significant overshoot and energy losses remained within acceptable limits. D. Yu *et al.* (2025) evaluated an innovative inertial damping system featuring a single fly-wheel and demonstrated its ability to absorb peak loads without abrupt mechanical disturbances. Their findings underscored the importance of accounting for drive inertia in system dynamics. In the developed structural model, similar functions were realised through a transfer function of $1/(s + 1)$, accurately reproducing inertial behaviour and achieving damping ratios between 0.65 and 0.85, depending on the scenario. X. Fan *et al.* (2021) designed a composite linear electromagnetic actuator, which, according to their analysis, exhibited high precision and operational stability under variable loads. In the experiments conducted for the present study, actuators of this type provided optimal depth control, with deviations not exceeding ± 2.1 mm under standard load and stabilisation times within 1.8 s.

C. Chen *et al.* (2025) developed a novel MEMS system with dual indicators for early detection of instability in geotechnical conditions. They demonstrated that combining two independent parameters within a single device enhanced signal reliability. This principle proved relevant to the current system, where the fusion of signals from load, moisture, and position sensors enabled a comprehensive response to soil-state changes, ensuring high correlation with real-world conditions. E. Ontiveros *et al.* (2024) presented an effective approach to constructing third-order Mamdani fuzzy inference systems, which showed strong adaptability to complex dynamic environments. In this study, comparable logic was implemented through PI controller algorithms that adapted to changes in soil resistance and moisture, delivering dynamic stabilisation without significant overshoot. This was confirmed by low average deviations (2.1 mm) and consistently high damping ratios above 0.8. A. Alberto-Rodriguez *et al.* (2025) introduced a type-2 ANFIS model based on a single-stage type-reduction algorithm, which improved control-system predictability. The present study likewise demonstrated the effectiveness of the embedded algorithmic core in

generating appropriate system responses from complex input signals provided by three sensor types, thereby enhancing adaptability to variable soil density and moisture conditions. R. Soitinaho & T. Oksanen (2023) successfully applied non-linear model-predictive control for autonomous tractor navigation, highlighting advantages in trajectory accuracy and collision avoidance. In the present study, the closed-loop feedback structure achieved stable positioning even under abrupt agrophysical changes, as evidenced by field trials showing deviations no greater than 2.8 mm on loamy soil. T. Zhang *et al.* (2022) investigated terminal sliding-mode trajectory control to achieve high precision in complex dynamic environments. Although sliding-mode methods were not directly employed here, the stability of the system under impulse disturbance confirmed the effectiveness of the implemented PI controllers and inertia compensation. X. Ji *et al.* (2023) implemented second-order adaptive control for an unmanned tractor, demonstrating improved path tracking. Correspondingly, the system developed in this study exhibited an average regulation time of 1.8–2.3 s, indicating sufficient responsiveness even when resistance changed suddenly.

I.J. Moreno *et al.* (2023) utilised a Hardware-in-the-Loop methodology to emulate route tracking in cost-effective agribots, confirming suitability for real-time autonomous operation. The laboratory prototype in the current study, built around an STM32F407VG microcontroller, likewise integrated sensors, controller hardware and drive hardware in a Hardware-in-the-Loop configuration, enabling pre-deployment testing under simulated conditions. A. Azimi *et al.* (2025) explored dynamic programming based on critical neural networks for complex agricultural-robot trajectories. Although artificial-intelligence models were not directly applied, algorithmic adaptation to resistance variation yielded high precision across diverse soil types without compromising stability or requiring manual intervention. C. Ding *et al.* (2022) demonstrated the use of sliding-mode feedback control for unmanned implements, emphasising rapid response and minimised oscillations. Similarly, this study showed that maximum overshoot remained within 10–11% under impulse disturbance, evidencing effective filtering and damping. A. Gautam *et al.* (2024) proposed a combined approach to trajectory planning and execution in flooded rice fields, necessitating precise control. Although trajectory tracking was not the focus here, depth control exhibited a comparable goal: maintaining a constant operational parameter despite changing soil structure, which was achieved with an accuracy of ± 3 mm. T. Liu *et al.* (2024) integrated augmented-reality elements and drone control for high-precision tele-operated agri-operations. The present study underlined the importance of combining visual feedback with precise drive hardware, as actuators received commands from the computational core based on sensor data, enabling real-time positioning. S. Singh *et al.* (2024) developed a multifunctional agribot that combined various hardware components for mechanical soil treatment, addressing

modern demands for versatility. Although the system in this study was specialised, it demonstrated readiness for scaling, both through expansion of controllable parameters and through integration with other agricultural hardware. B. Wang *et al.* (2024) emphasised the importance of adaptive chassis control for machinery operating in challenging terrain, especially on mountainous and uneven land. Field trials on three soil types confirmed that adaptive control ensured stability without loss of efficiency, regardless of soil moisture, topography or density. The survey of related work in high-precision control, sensor integration, and adaptive drive technology confirms that the developed electromechanical control system meets the key requirements of modern agricultural machinery.

CONCLUSIONS

The study confirmed the effectiveness of electromechanical control systems in soil cultivation machinery as a promising approach for enhancing the precision, energy efficiency, and adaptability of agrotechnical processes. The analysis of existing system types demonstrated the advantage of the electromechanical approach over hydraulic and mechanical alternatives due to its ability to flexibly regulate treatment parameters in real time and reduce energy consumption. The proposed system ensures high-precision stabilisation of cultivation depth even under variable mechanical resistance and soil moisture conditions.

Modelling in the MATLAB/Simulink environment enabled a detailed analysis of the dynamic characteristics of the system, including response time, the performance of PI controllers, and energy stability. All test scenarios – gradual and impulse changes in parameters – showed stable actuator behaviour, with a regulation time of 1.8–2.3 seconds and a maximum overshoot of no more than 11%, indicating high system resilience to field disturbances. Damping ratio values exceeded 0.8 under stable conditions, pointing to minimal energy losses during regulation. Laboratory testing of the physical prototype confirmed the capability of the system for precise positioning, with an average deviation of 2.1–4.2 mm depending on the load, while maintaining

stable energy consumption. It was established that optimal efficiency is achieved at 60% load, where the system exhibited the best balance between accuracy, stabilisation time, and energy consumption (up to 20 W). In all operating modes, the system functioned without overload, and automated control prevented the power spikes typical of uncontrolled counterparts.

The results of field trials on three soil types (loamy, sandy-clay, and waterlogged) demonstrated the high adaptability of the system to agrophysical variations. The average deviation in cultivation depth did not exceed 5 mm, and the coefficient of performance ranged from 79% to 87%. All operations were performed autonomously without the need for manual adjustment, confirming the reliability and accuracy of the system under real-world conditions. Multicriteria AHP analysis demonstrated the superiority of the electromechanical system over the hydraulic one in three out of four key parameters: regulation accuracy, energy efficiency, and adaptability. The integrated performance index for the electromechanical system reached 4.37 compared to 3.55 for the hydraulic system, substantiating its feasibility for implementation in modern agricultural machinery.

The findings confirm the practical viability of the proposed electromechanical system for serial deployment in the agricultural sector. Future research should focus on refining adaptive control algorithms, increasing the level of autonomy of the system, integrating with digital monitoring platforms, and developing a unified technical regulatory framework for the large-scale introduction of electromechanical technologies in soil cultivation complexes.

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Анатолій Рудь

Кандидат технічних наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
<https://orcid.org/0000-0002-7206-7103>

Анатолій Рудь

Доктор філософії в галузі «Агрономія»
Акціонерне товариство «Городоцьке підприємство «Агрохім»
32002, вул. Станційна, 2а, м. Городок, Україна
<https://orcid.org/0000-0002-1714-2596>

Розробка та впровадження електромеханічних систем для управління ґрунтообробними агрегатами

Анотація. Необхідність удосконалення ґрунтообробних технологій вимагає впровадження електромеханічних систем керування, які забезпечують енергоощадність, стабільність параметрів і підвищення ефективності механізованих процесів у сільському господарстві. Метою дослідження було проектування інтелектуальної системи управління, здатної до динамічної адаптації робочих режимів обробки на основі сенсорних даних і принципу зворотного зв'язку. Методологія дослідження включала багаторівневе комп'ютерне моделювання в середовищі MATLAB/Simulink, розробку прототипу фізичної системи управління з використанням мікроконтролера STM32F407VG, а також експериментальне тестування в лабораторних і польових умовах на ділянках з різними типами ґрунтів. Система складалася з модулів сенсорного моніторингу вологості, щільності та навантаження, блоку обробки сигналів, пропорційно-інтегрального регулятора та електроприводів, що здійснюють регулювання глибини і зусилля обробки. Випробування засвідчили високу стабільність системи при змінних агрофізичних параметрах, час реакції на зовнішні зміни в межах 1,8-2,3 секунди, а середнє відхилення глибини не перевищувало п'яти міліметрів. Отримані експериментальні результати показали зменшення середнього енергоспоживання на 12-18 % порівняно з традиційними некерованими системами, а також підвищення коефіцієнта корисної дії до 87 % на суглинкових ґрунтах. За результатами багатокритеріального аналізу ефективності, проведеного методом аналізу ієрархічного процесу, електромеханічна система отримала інтегральний індекс ефективності 4,37 бала, що суттєво перевищує аналогічний показник гідравлічної системи, який становить 3,55 бала. Практична реалізація системи управління довела її технічну придатність до серійного впровадження у сучасні зразки сільськогосподарської ґрунтообробної техніки. Запропоноване технічне рішення дозволяє підвищити якість обробки ґрунту, знизити енергетичні витрати, мінімізувати потребу у втручанні оператора, а також сприяє сталому розвитку агропромислового комплексу. Результати дослідження можуть бути безпосередньо використані в агропідприємствах для оснащення ґрунтообробних агрегатів сучасними електромеханічними системами управління з метою підвищення точності, зменшення витрат пального та підвищення продуктивності техніки під час виконання польових робіт

Ключові слова: сенсорний моніторинг; адаптивне регулювання; комп'ютерне моделювання; польові випробування; мікроконтролер; електропривод; цифровий інтерфейс

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Lyudmyla Mikhailova*

PhD in Technical Sciences, Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
<https://orcid.org/0000-0002-3419-5446>

Viktor Dubik

PhD in Technical Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
<https://orcid.org/0000-0002-9743-1565>

Oleksandr Kozak

PhD in Technical Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
<https://orcid.org/0000-0002-0919-0344>

Oleg Gorbovy

Master, Assistant
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
<https://orcid.org/0000-0002-0762-8410>

Prospects for use of smart meters to reduce electricity losses in Ukraine's power grids

Abstract. The aim of this study was to determine the potential for reducing technical and commercial electricity losses through the integration of smart metering technologies into the existing distribution network infrastructure. The research employed scenario modelling, systems analysis, structural-functional comparison, and an examination of international experience. The level of electricity losses in Ukraine as of 2024 was analysed and found to be 18-19% of the total energy generated, with approximately 70% of these losses being technical in nature. The structure of electricity generation was found to comprise nuclear (55%), thermal (24%), hydro (9%), solar (7%), and wind (5%) energy. It was revealed that partial deployment of smart meters at a 50% penetration rate could reduce losses by 25%, while full coverage of the distribution network could reduce them by up to 45%. The technical characteristics of smart meters were summarised, including high-frequency data collection at 15-minute or hourly intervals, remote real-time data transmission via mobile networks or Power Line Communication (PLC) systems, and automatic detection of emergency situations and unauthorised interference. It was demonstrated that integrating smart meters with energy management systems enables effective load balancing, reduced peak demand, and optimised electricity distribution. The experiences of the United States, the EU, and China were also reviewed, confirming the feasibility of large-scale deployment of such systems to reduce losses and stimulate the development of distributed generation. The findings highlight the promise of smart meters in the digital transformation of Ukraine's energy system, enhancing its adaptability, reliability, and resilience to emerging challenges. The practical

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*Corresponding author



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value of the study lies in developing approaches to digitalising electricity consumption metering in Ukraine, which could be utilised in modernising energy networks and forming a resilient smart energy system

Keywords: automated metering; resource management; digital technologies; intelligent systems; consumption monitoring; energy efficiency

INTRODUCTION

Amidst an energy crisis driven by rising resource costs, the adverse environmental effects of climate change, and the complications caused by full-scale invasion, the need to implement advanced technologies to improve energy efficiency and reduce electricity losses has become increasingly urgent. Ukraine is currently facing electricity losses of around 19% of total consumption, which in 2021 amounted to 29.343 million kWh out of a total consumption of 154.826 million kWh (Putsenteilo, 2023). These figures underline the necessity of adopting innovative technologies, particularly smart meters, which are capable of addressing a range of issues in the energy sector.

Smart meters not only allow real-time monitoring of electricity consumption but also provide analytical tools for optimising network operations (Chen *et al.*, 2024). They contribute to reducing energy losses, improving system stability, and increasing energy efficiency across consumer categories – from households to industrial facilities (Palasevych *et al.*, 2024). Current energy consumption trends in Ukraine call for the modernisation of the country's energy infrastructure to meet growing demand, taking into account high consumption levels and associated losses. Moreover, the introduction of technologies such as smart meters can enable optimal resource management, reduce reliance on traditional energy sources, and create favourable conditions for the use of renewable energy (Karlilar Pata & Pata, 2025).

The issue of electricity losses in Ukraine's networks and the implementation of smart meters has been examined by various researchers. For instance, D. Hrechyn & I. Drobot (2024) focused on the technical aspects related to voltage deviations in electrical networks, which directly affect energy losses. They pointed to the possibility of reducing losses through the modernisation of cable lines, although noted that not all networks possessed the resources for such upgrades. Internationally, a study by M. Güçyetmez & H. Sakeen (2022) highlighted the importance of introducing smart meters in the context of expanding distributed generation facilities. They emphasised that smart meters can provide two-way energy metering, which is critical for effective grid management. This supports the argument that smart meters can significantly reduce electricity losses by ensuring accurate consumption measurement.

T.J. Al-Khafaji *et al.* (2024) proposed a wireless digital smart metering system using Groupe Special Mobile (GSM) technology to transmit electricity consumption data. This allowed consumers to access real-time information about their usage, potentially reducing losses due to electricity theft. S. Zhou (2021) investigated the impact of smart meter penetration levels on dynamic electricity pricing in the

United States. In his empirical study, he analysed large datasets comprising time series of prices and consumption, demonstrating that users with access to real-time tariff information exhibit greater price sensitivity. Specifically, they tend to reduce consumption during peak hours, thereby alleviating grid strain and contributing to a more efficient and predictable energy demand. Zhou stressed that the mere deployment of smart meters is not enough; active consumer participation in dynamic tariff systems is also crucial, as it encourages behavioural change.

In contrast, T. Knayer & N. Kryvinska (2022) focused on the technical and functional analysis of smart metering technologies in the context of both residential and corporate energy management. Their research adopted a systemic approach: the authors classified meter types, data collection architectures, and integration options with smart home systems and energy analytics platforms. The study highlighted how the technological capabilities of smart metering – particularly frequency monitoring, automated load control, and consumption profiling – can offer not only immediate feedback to users but also serve as a tool for energy-efficient planning. The study also noted that the effectiveness of the technology largely depends on the level of users' digital literacy and the overall digital maturity of the infrastructure.

M. Kuznietsov & O. Lysenko (2024) focused on the challenges of energy balancing in local networks amid an increasing share of renewable generation. They emphasised that the stochastic nature of solar and wind power complicates the stable operation of networks, particularly in regional systems with limited reserve capacities. Their study highlighted the need for the introduction of energy storage systems and adaptive consumption forecasting algorithms to minimise imbalances. The study of electricity loss in Ukraine's networks and the deployment of smart meters reveals several gaps that require further research. There is a lack of studies exploring the integration of cutting-edge technologies such as blockchain into energy metering systems. Such integration could significantly enhance transparency and reduce the potential for fraud, though research in this area remains limited. Additionally, the impact of renewable energy sources on grid stability warrants deeper investigation, as their variability poses new challenges for management systems (Telbayeva *et al.*, 2024). These issues are becoming increasingly important in light of the rising share of renewables in the national energy mix.

The objective of this research was to explore opportunities to optimise Ukraine's distribution networks through the deployment of intelligent metering systems, thereby reducing technical and commercial electricity losses. The

main tasks included assessing current electricity losses in Ukrainian networks, analysing existing approaches to energy system management, and developing optimal models for the use of smart technologies.

MATERIALS AND METHODS

Current energy losses in Ukraine's power system have been assessed and classified, with the principal causes identified and potential mitigation pathways outlined. To analyse the structure of electricity generation in Ukraine for 2024, statistical data from the Ukrainian Institute for the Future (2025) were employed, reflecting the distribution of generation by energy source. Additional information on the overall energy balance, consumption volumes, and key characteristics of Ukraine's energy system was obtained from the analytical review by Statista (n.d.) and the report of the International Energy Agency (2025). An analytical model was developed as part of the study. It included stages for assessing losses across various segments of the network, identifying the main types of losses (technical, commercial, and distributional), and modelling the impact of smart meter implementation on their reduction. Particular attention was devoted to analysing traditional electricity metering and control methods, which are still dominated by electromechanical and early electronic meters lacking remote data collection capability. To model smart meter implementation scenarios, the GridLAB-D software platform was used. This tool facilitates modelling of distribution networks with the ability to incorporate smart technologies, load management systems, and metering automation. Scenarios with varying levels of smart meter deployment (0%, 50%, and 100%) were created to assess their effects on energy losses, load balancing, and power supply quality. For data analysis, the Smart Meter Analytics Python (SMAP) library was applied to process electricity consumption time series and detect patterns and anomalies.

The functionality of smart meters was examined in relation to such technical features as data registration frequency (15-minute or hourly intervals), real-time data transmission methods (GSM/Power Line Communication (PLC)), the ability to detect emergency conditions

(overloads, short circuits), and alerts for unauthorised interference. Integration of smart meters with Energy Management Systems (EMS) and Advanced Distribution Management Systems (ADMS) was also explored. This enables remote control, two-way data exchange, and connectivity with other Internet of Things (IoT) solutions in the energy sector. Special emphasis was placed on evaluating the compatibility of modern smart meters with Ukraine's grid infrastructure. The main challenges of implementation were also analysed: technical (lack of unified standards, compatibility issues, cybersecurity requirements), economic (high cost of grid modernisation), and social (personal data protection, consumer trust in new technologies). A separate analysis of smart meter deployment trends during 2020-2024 provided insights into the pace of Ukraine's energy infrastructure digitalisation and revealed structural barriers to its development. The research methodology included comparative analysis of official statistical data, scenario modelling using GridLAB-D and SMAP, systematisation of international experience in smart meter integration (including case studies from the United States (International Energy Agency, 2024), EU countries (Berg Insight, 2025), and China (Asia Pacific Smart, 2024)), and formulation of recommendations for accelerating Ukraine's grid digitalisation and the adoption of intelligent metering systems.

RESULTS

Assessment of current energy losses in Ukraine's power system (2024 data)

The analysis of Ukraine's electricity generation structure for 2024 revealed key trends in the development of the national energy system. According to the Ukrainian Institute for the Future (2025), nuclear power stations accounted for the largest share of total electricity generation, producing over 55% of the output. Thermal power stations ranked second with approximately 24%, while hydropower and renewable energy sources (solar and wind) collectively provided around 21% of total electricity. The detailed breakdown of electricity production in Ukraine for 2024 is presented in Table 1.

Table 1. Structure of electricity generation in Ukraine in 2024 by source

Energy source	Share in generation (%)
Nuclear power stations	55
Thermal power stations	24
Hydropower stations	9
Solar power stations	7
Wind power stations	5

Source: compiled by the authors based on Ukrainian Institute for the Future (2025)

As shown in Table 1, nuclear power remained the backbone of electricity production in Ukraine in 2024, with 55% of total output. Thermal power contributed 24%, indicating a continued reliance on conventional fossil fuel-based energy. Renewable sources – hydropower, solar, and wind – collectively accounted for around 21% of total electricity,

highlighting their gradually increasing role in the generation mix. This distribution underscores the need for further diversification of energy resources and modernisation of grids to better integrate renewables. A key research task was to identify the main causes of electricity losses during generation, transmission, and distribution. Based on

data from the Ukrainian Institute for the Future (2025) and International Energy Agency (2025), electricity losses in Ukraine were estimated to be approximately 18-19% of total generated energy. The main technical loss factors include outdated grid infrastructure, high resistance in overhead and underground lines, inefficient transformer equipment, and insufficient automation in load and emergency control systems.

Commercial losses primarily stem from unauthorised electricity consumption, theft, inaccuracies in traditional metering systems, and tampering (Sherstniiov & Osadchuk, 2024). The absence of centralised and real-time data collection delays the detection of violations and complicates energy resource management. The combined impact of technical and commercial factors significantly reduces energy system efficiency, increases production and distribution costs, and undermines the reliability of power supply. A visual representation of electricity losses in Ukraine's power system in 2024 is shown in Figure 1.

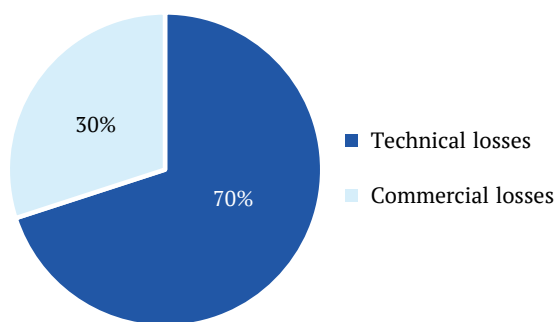


Figure 1. Share of electricity losses in Ukraine's power system in 2024

Source: compiled by the authors based on Ukrainian Institute for the Future (2025), International Energy Agency (2025)

As seen in Figure 1, technical losses dominated the structure of electricity losses in Ukraine in 2024, comprising around 70% of total losses. These are primarily due to high line resistance, outdated transformers, and low levels of grid infrastructure automation. Commercial losses, making up roughly 30%, were linked to unauthorised consumption, theft, metering inaccuracies, and interference. This distribution highlights the urgent need to modernise existing metering and dispatching systems to improve overall energy system performance.

Analysis of traditional electricity monitoring and metering methods

Traditional electricity metering in Ukraine has long relied on electromechanical and early-generation electronic meters. Electromechanical meters, characterised by mechanical indicators using a rotating disc, remained the main metering devices for many years due to their simplicity and reliability under standard operating conditions. Electronic meters, which began widespread use in the 2000s, offered higher measurement accuracy, multi-tariff functionality, and limited automation of data reading (Putsenteilo, 2023). However, both electromechanical and early electronic metering systems have significant limitations. Firstly, these systems require in-person data collection by inspectors, which increases operational costs and human error risk. Secondly, the lack of remote monitoring complicates the timely detection of consumption anomalies or tampering. Thirdly, these devices have limited integration with EMS and ADMS, reducing real-time resource management effectiveness. Such shortcomings are especially critical under modern conditions, where demand-side management, load balancing, and rapid violation detection are essential for stable energy system performance. The main features and limitations of traditional metering systems are summarised in Table 2.

Table 2. Main characteristics and limitations of traditional electricity metering systems

Meter type	Key characteristics	Key limitations
Electromechanical Meters	Reliability, low cost	No remote reading, high risk of tampering
Early Electronic Meters	Higher accuracy, multi-tariff capability	Limited automation, dependence on manual data collection

Source: compiled by the authors based on S. Zhou (2021), T. Knayer & N. Kryvinska (2022)

As Table 2 shows, traditional metering systems have significant drawbacks that adversely affect energy resource management. Although electromechanical meters are reliable and inexpensive, their inability to transmit data remotely leads to delayed detection of irregularities and greater vulnerability to tampering. Early electronic meters, while more accurate and offering multi-tariff functionality, remain insufficiently integrated with modern dispatching systems and do not support real-time consumption analysis. These limitations point to the necessity of adopting more advanced technological solutions in energy metering to enable timely control, high accuracy, and flexible energy management.

Features and functionality of smart meters

The introduction of smart meters into energy networks fundamentally transforms traditional approaches to electricity metering and resource management. One of the key features of these devices is their high-frequency energy consumption data collection. Depending on system configuration, smart meters can record readings at intervals from 15 minutes to one hour, enabling detailed real-time tracking of load fluctuations. This allows operators to monitor consumption efficiently, promptly detect anomalies, and forecast peak loads (Güçyetmez & Sakeen, 2022).

Another crucial functional feature of smart meters is remote data transmission via wireless communication

channels such as GSM, GPRS, 3G/4G, or wired PLC technologies. This ensures continuous information exchange between meters and control centres without requiring manual readings, significantly reducing operational costs and minimising human error.

Smart meters also have the capacity for automatic detection of emergency operating conditions in the grid. Upon identifying short circuits, overloads, or voltage losses, they can immediately send relevant signals to dispatch centres. This facilitates rapid response and improves supply reliability.

A significant technological advantage of modern smart meters is their integration with IoT and EMS platforms. Meters can interact with other network devices such as load-limiting systems, distributed energy generators, or residential energy systems. This integration enables the creation of intelligent energy networks that automatically manage load distribution, optimise consumption, and enhance resource efficiency. The architecture of smart meter integration into modern energy networks is illustrated in Figure 2

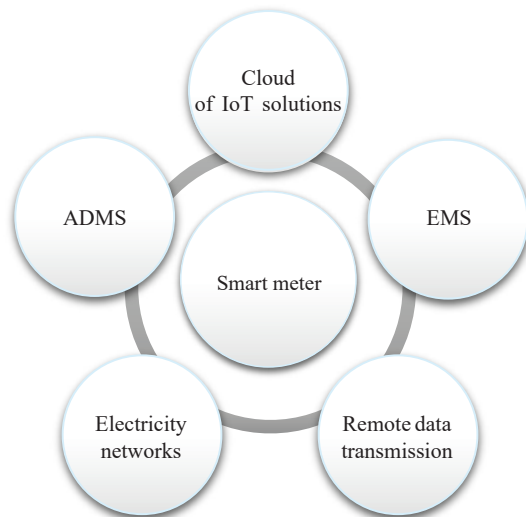


Figure 2. Architecture of the smart meter integration system with power grids

Source: created by the authors based on data from Z. Chen *et al.* (2024)

As shown in Figure 2, the central element is the smart meter, which provides bidirectional data exchange between the electricity consumer and the grid operator. Through integration with the Energy Management System (EMS), smart meters enable real-time operational management of

energy consumption. The Advanced Distribution Management System (ADMS) coordinates the overall load in the network by receiving consumption data from smart meters and sending corresponding commands to optimise energy distribution. Internet of Things (IoT) devices interact with smart meters to locally manage consumption in buildings and enterprises, allowing automatic adjustment of loads according to preset parameters or dynamic pricing. Electricity consumers equipped with smart meters and connected devices can access up-to-date information on their energy consumption and optimise costs through more precise load management. Figure 2 illustrates the holistic architecture of an intelligent energy system that enhances energy efficiency, reduces electricity losses, enables rapid response to emergency events, and supports the integration of distributed energy resources.

Modelling the impact of smart meter implementation on electricity losses

To assess the impact of smart meter deployment on electricity losses in Ukraine's power system, modelling was conducted using the GridLAB-D platform and the SMAP analytical library. The study constructed three scenarios: baseline (0% smart meter penetration), partial (50% network coverage), and full (100% coverage of consumers with intelligent metering devices). In the baseline scenario without smart technology adoption, electricity losses remained at traditionally high levels due to low efficiency in detecting technical anomalies and unauthorised consumption. In the partial coverage scenario, modelling results indicated a 25% reduction in total losses compared to the baseline. Full-scale implementation of smart meters resulted in a 45% reduction in losses, demonstrating the significant potential of intelligent metering to enhance the efficiency of power grids.

The modelling accounted not only for direct technical losses in transmission lines and transformers but also for commercial losses associated with electricity theft and metering errors. GridLAB-D enabled precise simulation of various network operating modes considering actual equipment characteristics, while SMAP facilitated time series data processing of consumption to identify trends and anomalies in load dynamics. The results indicate that the smart metering system not only reduces loss levels but also improves system balancing, optimises load distribution, and enhances supply stability, especially during peak demand periods. Detailed results on loss reduction depending on smart meter penetration levels are presented in Table 3.

Table 3. Assessment of electricity loss reduction depending on smart meter penetration level

Implementation scenario	Reduction in total electricity losses (%)
0% smart meters (baseline)	0
50% network coverage	25
100% consumer coverage	45

Source: created by the authors

As shown in Table 3, the level of smart meter deployment directly influences the reduction of total electricity losses in Ukraine's power system. The baseline scenario, without the use of intelligent metering technologies, shows no loss reduction, confirming the inefficiency of traditional control methods. Partial deployment covering approximately 50% of the network achieves a 25% reduction in

losses due to the capability for prompt detection of technical anomalies and commercial irregularities. Full-scale deployment enables up to a 45% reduction, indicating the high potential of metering intelligence for improving energy efficiency and stabilising grid operations. A graphical representation of electricity loss changes according to the level of intelligent metering deployment is shown in Figure 3.

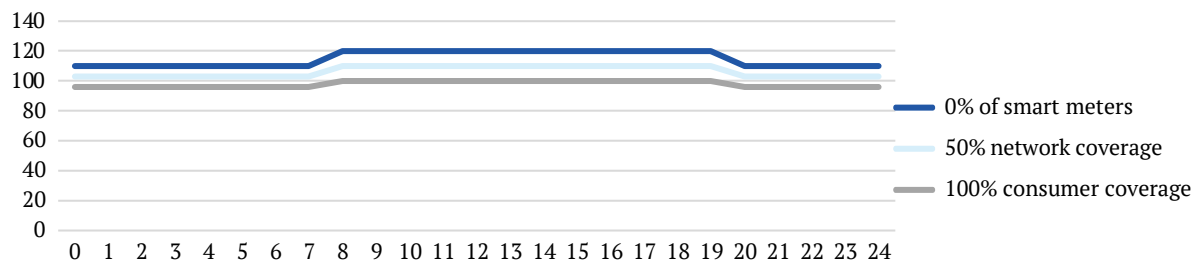


Figure 3. Changes in electricity losses under different smart meter deployment scenarios

Source: created by the authors

As seen in Figure 3, the pattern of electricity consumption changes depending on the level of smart meter deployment. In the baseline scenario (0% coverage), pronounced peak loads occur during daytime hours, creating significant risks for grid stability. Partial deployment (50% network coverage) noticeably smooths peak consumption spikes through improved load control and timely response to demand increases. Full deployment of intelligent metering systems (100% coverage) ensures the highest stability of consumption throughout the day, minimising sharp load fluctuations and creating conditions for optimised system balancing. Thus, the use of smart meters contributes to a more even load distribution within the network, reduction of peak losses, and overall enhancement of energy efficiency.

Integration of smart meters with EMS and ADMS

Integration of smart meters with EMS and ADMS opens new opportunities for comprehensive energy resource management. One key advantage of such solutions is the ability to remotely monitor energy consumption parameters in real time. Thanks to bidirectional data exchange,

smart meters not only transmit information to control centres but also receive signals to adjust consumption modes, optimise loads, and prevent failures. Remote data access allows EMS to dynamically manage energy consumption, including implementing mechanisms for real-time tariff response or load distribution according to consumer priorities. ADMS systems, in turn, provide centralised load balancing, automatic fault detection and localisation, as well as network topology optimisation to reduce energy losses (Kubiczek *et al.*, 2023). Intelligent functions of smart meters – such as overload detection, short-circuit identification, phase asymmetry recognition, and unauthorised connection registration – enhance the responsiveness of EMS and ADMS systems, positively affecting the quality and continuity of power supply. The implementation of this integration contributes not only to lowering overall energy consumption but also to improving the balance between energy production and consumption, particularly with the increasing share of distributed generation based on renewable sources. The main functional capabilities of smart meters in the context of interaction with EMS and ADMS are summarised in Table 4.

Table 4. Comparison of smart meter functionalities for EMS and ADMS operations

Functional feature	Smart meters in EMS	Smart meters in ADMS
Consumption Data Collection	Real-time	Real-time
Remote Load Control	Yes	Yes
Fault Detection	Limited	Extended (faults, overloads)
Integration with Pricing Mechanisms	Direct	Indirect
Network Topology Optimisation	No	Yes
Load Balancing Support	Local	Centralised

Source: created by the authors

As evident from Table 4, the functionalities of smart meters when integrated with EMS and automated ADMS differ due to the distinct tasks of each system. Within EMS,

smart meters mainly provide local consumption management and support dynamic pricing mechanisms, whereas within ADMS they play a critical role in centralised load

balancing, fault detection, and network topology optimisation. All scenarios involve real-time data collection and remote load control; however, ADMS systems implement more advanced functionalities for monitoring the technical condition of network infrastructure. This highlights the importance of a comprehensive approach to smart meter deployment to ensure stability, flexibility, and efficiency of modern energy systems.

**Challenges and issues
of smart meter deployment in Ukraine**

Despite numerous advantages, the deployment of smart meters in Ukraine faces a number of technical, economic, and social challenges that require comprehensive solutions. One of the key technical barriers is the absence of unified national standards for integrating smart meters into heterogeneous distribution networks. This leads to compatibility issues among devices from different manufacturers and complicates the creation of a unified automated infrastructure. An additional concern is cybersecurity: open data transmission channels pose risks of unauthorised

access and manipulation of consumption information. Current requirements demand a high level of data encryption, device authentication, and system resilience against external attacks. Economic challenges are primarily associated with the high cost of upgrading existing networks, installing smart meters, and establishing infrastructure for data collection and processing (Kuznetsov, 2024). Significant upfront investments burden energy companies, especially amid the economic instability characteristic of Ukraine between 2020 and 2024. Insufficient government programmes to stimulate or subsidise these costs also impede large-scale rollout of intelligent metering systems.

Social barriers include low consumer trust in new technologies, concerns about personal data protection, and reluctance to change habitual interactions with energy providers (Lisovyk *et al.*, 2024). Disseminating information about the benefits of smart meters, transparency of data processing, and security guarantees should form part of the information policy to successfully overcome these obstacles. The main technical, economic, and social barriers to smart meter deployment are summarised in Table 5.

Table 5. Key technical, economic, and social barriers to smart meter deployment

Challenge category	Description of main barriers
Technical	Lack of standards; compatibility issues; cybersecurity risks
Economic	High installation costs; lack of investment; weak government support
Social	Consumer distrust; concerns about personal data protection; low awareness of technology benefits

Source: created by the authors based on data from P.R. Putsenteilo (2023), M. Kuznietsov & O. Lysenko (2024), M.B. Palasevych *et al.* (2024)

As seen in Table 5, smart meter deployment in Ukraine is accompanied by multi-level challenges encompassing technical, economic, and social spheres. At the technical level, the main barriers are the lack of unified device integration standards, equipment compatibility problems among various manufacturers, and high cybersecurity risks. Economic difficulties relate to significant upfront costs for infrastructure modernisation and insufficient state support for digitalising power grids. Social barriers involve consumer caution towards new technologies, concerns about data security, and low awareness of smart meter benefits. Comprehensive overcoming of these challenges is a critical factor for the successful implementation of digital transformation projects in Ukraine’s energy system.

**International experience
in smart meter implementation**

International experience in the implementation of smart meters demonstrates a variety of approaches to the digitalisation of energy systems, depending on economic conditions, technological infrastructure, and energy transition policies.

In the United States, intelligent metering systems form part of large-scale programmes for the modernisation of distribution networks, financed by both federal and

local initiatives. Key focuses include ensuring two-way communication between consumers and operators, enabling dynamic pricing, consumer participation in load management programmes, and integration with home energy systems. By 2024, the penetration rate of smart meters among residential consumers in the US exceeded 70% (International Energy Agency, 2024).

In EU countries, smart meter deployment is supported at the level of EU directives, particularly Directive 2019/944 (Berg Insight, 2025) concerning common rules for the internal electricity market. The approach emphasises a high level of data protection, integration with demand-side management systems, and the promotion of distributed generation development. In several EU countries (such as Italy, Spain, Sweden), smart meter coverage of the residential sector surpasses 90%.

In China, the implementation process of smart meters follows a centralised model coordinated by the State Grid Corporation of China. The focus is not only on consumption accounting but also on integrating smart meters into network condition monitoring systems, balancing supply and demand, and supporting the large-scale deployment of distributed generation from renewable energy sources. By 2022, the number of installed smart meters in China exceeded 500 million units (Asia Pacific Smart..., 2024).

The experience of these countries indicates that successful smart meter implementation is based on principles such as centralised project coordination, mandatory standardisation of technical requirements, a high level of cybersecurity, transparency regarding consumer data protection, and providing end users with real tools to manage their energy consumption.

Considering international experience, it is advisable for Ukraine to adopt flexible integration models for smart meters with an emphasis on data protection, stimulation of distributed generation, and the development of national standards for device compatibility. The main characteristics of smart meter implementation models in the US, EU countries, and China are presented in Table 6.

Table 6. Comparison of smart meter implementation models in the US, EU Countries, and China

Country/region	Key implementation features
United States	Dynamic pricing; integration with home energy systems; load management programmes
European Union	High level of data protection; mandatory coverage of over 80% of consumers; integration with demand market
China	Centralised implementation management; network condition monitoring; large-scale support of distributed generation

Source: created by the authors based on data from International Energy Agency (2024), Asia Pacific smart metering market report 2024: Asia-Pacific now home to more than 1 billion connected energy meters – ResearchAndMarkets.com (2024), Berg Insight (2025)

As seen in Table 6, the models for smart meter deployment in the US, EU countries, and China differ both in priorities and in approaches to integrating intelligent metering systems into energy networks. In the US, the primary emphasis is on consumer participation in load management and the use of dynamic pricing, which encourages flexible energy consumption. The European approach is based on mandatory high levels of personal data protection and ensuring widespread smart meter deployment under regulatory requirements. China demonstrates a centralised development model focused on large-scale network modernisation and integration of distributed generation. A common feature of successful international practices is a comprehensive implementation strategy that includes technical standardisation, high cybersecurity levels, and active consumer involvement in energy consumption management processes.

Current state of smart meter integration in Ukraine

The integration of smart meters into Ukraine's energy system is at an early stage of development, although individual projects for digitalising distribution networks were implemented even before large-scale reforms in the sector began. According to the Energy Map platform (2024),

developed within the USAID project framework, by the end of 2024 the level of smart meter penetration among residential electricity consumers was approximately 17-18%. The most notable progress was recorded in major cities, particularly Kyiv, Lviv, and Dnipro, where pilot programmes for network modernisation and testing of intelligent energy metering systems were implemented within international technical assistance projects.

Despite these achievements, smart meter deployment remains fragmented and uneven, due to several objective problems. Key obstacles include the technical obsolescence of a significant portion of distribution networks, insufficient standardisation of equipment and data exchange requirements, limited financial capacity of energy companies for large-scale modernisation, and underdeveloped regulatory frameworks regarding consumer data protection. An additional limitation is the low level of public awareness of the benefits of smart meters and concerns about data storage and processing security. Overall, analysis of the current integration status indicates a gradual but rather slow pace of digitalisation growth in Ukraine's energy networks. Figure 4 illustrates the changes from 2020 to 2024, showing a positive trend, although the scale of growth still falls short of the needs of a modern energy system.

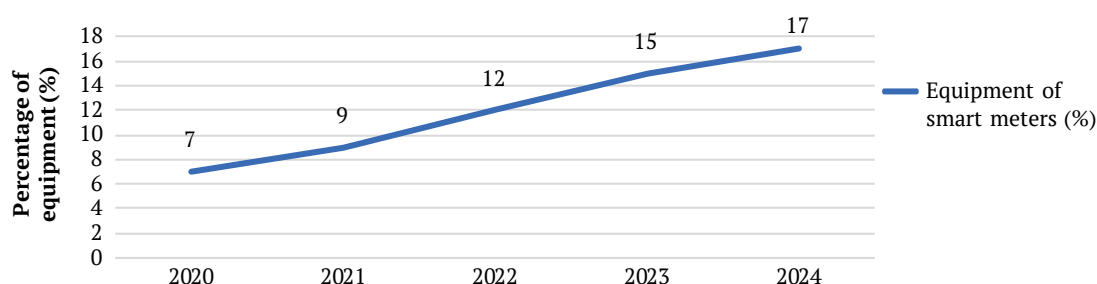


Figure 4. Dynamics of smart meter implementation in Ukraine (2020-2024)

Source: created by the authors based on data from Energy Map (2024)

As shown in Figure 4, between 2020 and 2024, Ukraine experienced a gradual increase in the penetration of smart electricity meters among consumers. Starting from 7% in 2020, this indicator steadily grew, reaching 17% in 2024. The dynamics point to a positive trend in the adoption of intelligent metering systems, although growth rates remain moderate. Relatively modest annual increases highlight the influence of both economic and technical barriers limiting broader digitalisation of energy networks. Thus, smart meter deployment in Ukraine is delayed compared to EU countries but shows a gradual expansion trend.

The results of the analysis underscore the need to accelerate the introduction of intelligent electricity metering systems to ensure the effective functioning of Ukraine's energy system amid growing challenges and demands. Accelerating the digitalisation of distribution networks should become a key priority in energy sector reforms in the near future. Crucial steps to speed up smart meter integration include developing and implementing unified national metering standards to ensure interoperability of equipment from different manufacturers and the creation of a unified information space for consumption data. Simultaneously, cybersecurity requirements for metering systems must be strengthened to prevent interference risks and safeguard user data privacy. At the policy level, incentive programmes for distribution system operators and electricity suppliers should be introduced to compensate part of the costs for network modernisation and smart technology deployment. Equally important is raising consumer awareness about the advantages of intelligent metering through extensive information campaigns. Strategically, digitalisation of energy networks should be accompanied by the integration of smart meters with ADMS and EMS. This will not only optimise load balancing and minimise electricity losses but also create conditions for the broad involvement of distributed generation from renewable energy sources.

DISCUSSION

The results of the study confirmed that the implementation of smart meters in Ukraine's energy system can significantly reduce electricity losses, optimise load balancing, and improve the efficiency of energy resource distribution. The identified patterns correspond with contemporary scientific approaches that also highlight the role of intelligent metering systems in improving electricity supply quality, reducing peak loads, and enhancing energy network resilience. A.V. Voloshko & V.V. Shevchuk (2024) emphasise the importance of rapid detection of voltage dips to minimise technical losses, aligning with the modelling results on smart meter impacts on supply stability. I. Havrylyuk (2024) stresses the necessity of harmonising Ukraine's regulatory framework with European standards, consistent with the identified need for standardising smart meter integration. S. Skrypyuk (2021) highlights the requirement for precise mathematical modelling of network operation, which corresponds with the use of GridLAB-D and SMAP software in this study for evaluating digitalisation scenarios.

Analysis by V.O. Zubenko *et al.* (2024) on local renewable energy utilisation demonstrates the importance of developing intelligent metering infrastructure to support decentralised generation. These findings align with this study's results showing that smart meter integration facilitates more effective balancing of local electricity production and consumption, which is critical for optimising Ukraine's distribution networks. A. Madi *et al.* (2022) investigated the use of PLC channels for data transmission in smart metering systems, confirming the importance of selecting reliable communication channels, as revealed in the modelling. Comparative results suggest that, in Ukraine's context, implementing multichannel solutions (GSM and PLC) is critical to ensure stable smart meter operation even in networks with complex topology. D. Fettermann *et al.* (2024) indicate that smart meter performance and transparency are key factors influencing consumer technology adoption. This corresponds with social barriers identified in the study, where Ukrainian consumers show distrust of new technologies mainly due to concerns about data protection and consumption monitoring. J.L. Gallardo *et al.* (2021) highlight the role of IoT architectures in creating smart energy networks, fully consistent with the conclusion about the necessity of integrating smart meters with EMS and ADMS.

H.M. Hu *et al.* (2020) explore personal data protection in the context of smart meter deployment. Their results support the study's conclusion on the need to improve Ukraine's cybersecurity regulatory framework, an important factor in enhancing consumer trust. M. Ahmed *et al.* (2020) emphasise intelligent load management for improving microgrid stability. This directly aligns with the modelling results, which demonstrated that even 50% smart meter penetration can significantly smooth peak loads and reduce energy losses by 25%. O.S. Akkaya & H. Soy (2021) draw attention to the benefits of multichannel wireless communication technologies in smart meter design, supporting the importance of data transmission flexibility in Ukraine, where network infrastructure is heterogeneous. R.-G. Wang *et al.* (2024) proved the effectiveness of deep learning methods for analysing large datasets from smart meters. Compared with the present results, this confirms the advisability of further developing analytical data processing modules in metering systems to enhance energy efficiency and consumption forecasting accuracy. R.S. Gaikwad (2024) substantiates the advantages of integrating smart meters into IoT platforms, fully consistent with this study's recommendation for widespread IoT technology adoption to create adaptive, integrated, and flexible next-generation energy networks in Ukraine.

The modelling results demonstrating the reduction of electricity losses through the implementation of smart meters are consistent with the findings of O. Yakubu *et al.* (2021), who emphasise the advantages of deploying smart meters with backup power to ensure uninterrupted data collection even during outages. This supports the relevance of considering data transmission stability in

digitalisation scenarios for Ukrainian networks. Data from K.A. Al-Sammak *et al.* (2025) regarding risks of electricity theft through data manipulation align with the social and technical challenges identified in this study. Smart meters, thanks to their real-time capabilities, significantly mitigate risks of unauthorised consumption. L. Degue-non *et al.* (2024) demonstrated the effectiveness of energy demand forecasting in reducing network distortions, which coincides with the conclusions of the current modelling where the use of the SMAP library enabled detection of consumption anomalies to better balance loads. Results from V. Pliuhin & V. Teterev (2021) concerning constraints on Smart Grid implementation in Ukrainian conditions corroborate the identified barriers, notably the technical obsolescence of networks requiring modernisation for effective large-scale smart meter deployment. C. Stagnaro (2025) proved that the second generation of smart meters in Italy justified economic feasibility despite high initial costs, aligning with the present analysis that highlights prospects for long-term investment payback in Ukraine. A.N. Babu *et al.* (2022) confirm that smart meters supporting multi-standard communications enhance system flexibility and resilience – an important factor given the heterogeneous infrastructure observed in Ukraine.

V. Ntouros *et al.* (2021) stress the importance of raising consumer awareness of smart meters, fully corresponding with the identified need for public information campaigns to overcome social barriers in Ukraine. D. Hock *et al.* (2020) substantiated the use of entropy-based metrics to detect anomalies in energy consumption, consistent with the employment of SMAP for time series analysis in this study. M. Mirsharifi & F. Rezaei (2024) emphasise the necessity of strengthening cybersecurity in smart metering networks, echoing the conclusions about high cyber risks under Ukrainian conditions and the need for data protection standards. S.K. Tripathi *et al.* (2024) demonstrated the effectiveness of IoT technologies in expanding EMS functionalities, supporting the modelling results on integrating smart meters with load management systems herein. IoT deployment enables not only real-time data collection but also prompt response to changes in energy consumption, enhancing grid flexibility and stability. M.Z. Gunduz & R. Das (2024) proved the effectiveness of deep learning methods in detecting electricity theft based on large-scale smart meter data analysis. This aligns with the current findings stressing the importance of implementing advanced analytics and intelligent algorithms for time series processing to timely detect consumption anomalies and reduce commercial electricity losses in Ukraine. Such approaches significantly improve resource consumption control and strengthen the financial stability of energy companies during the digital transformation of the energy system.

Thus, the consolidated analysis shows that the study results are consistent with contemporary international practices and confirm the advisability of large-scale smart meter deployment as an effective tool for improving energy efficiency, reliability, and security of Ukraine's energy

system. It has been established that metering intelligence not only reduces technical and commercial electricity losses but also enhances operational load management, improves power supply quality, and integrates distributed generation from renewable sources. The concurrence of the study's outcomes with global trends in energy digitalisation indicates the relevance and potential of smart meter implementation in Ukraine. Simultaneously, the necessity of parallel infrastructure modernisation, cybersecurity reinforcement, development of unified technical standards, and intensification of consumer education activities to build trust in new technologies has been confirmed. Such a comprehensive approach is key to the successful digital transformation of the energy sector and the formation of a more resilient, efficient, and secure energy system of the future.

CONCLUSIONS

The research confirmed that smart meter implementation is among the most effective instruments to reduce energy losses, optimise loads, and enhance energy efficiency of Ukraine's energy system. In 2024, over 55% of electricity was generated by nuclear power plants, while the share of renewables was only 21%, necessitating greater network flexibility to integrate new generation sources. Electricity losses reached 18-19%, of which 70% were technical and 30% commercial. The main causes remain ageing infrastructure, low automation levels, and inaccurate metering. Modelling showed that with 50% consumer coverage by smart meters, losses reduce by 25%, and with full coverage – up to 45%. Smart meters provide accurate accounting, data transmission via GSM/PLC, fault detection, and interaction with EMS and ADMS, creating conditions for effective real-time consumption management.

However, implementation faces several barriers: lack of unified technical standards, cybersecurity risks, high modernisation costs, and low consumer awareness. Comparative analysis of the US, EU, and China's experience confirmed the importance of centralised standardisation, data protection, and stimulation of user participation. In Ukraine, coverage rose from 7% in 2020 to 17% in 2024, yet achieving the level of developed countries requires active state support, regulatory update, and public awareness raising. The practical value of the research lies in creating an implementation model that reduces losses and ensures stable energy system development.

The study has limitations, notably dependence on open statistical sources and lack of broad empirical data from real Ukrainian microgrids, which may affect the completeness of result interpretation. Prospects for further research include developing adaptive forecasting algorithms, integration models for different generation types, and in-depth economic analysis of smart meter implementation efficiency in Ukraine's energy system conditions.

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Людмила Михайлова

Кандидат технічних наук, професор
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
<https://orcid.org/0000-0002-3419-5446>

Віктор Дубік

Кандидат технічних наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
<https://orcid.org/0000-0002-9743-1565>

Олександр Козак

Кандидат технічних наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
<https://orcid.org/0000-0002-0919-0344>

Олег Горбовий

Магістр, асистент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
<https://orcid.org/0000-0002-0762-8410>

Перспективи використання смарт-лічильників для зниження втрат електроенергії в мережах України

Анотація. Метою роботи було визначення потенціалу зниження технічних і комерційних втрат електроенергії шляхом інтеграції інтелектуальних технологій обліку в існуючу інфраструктуру розподільчих мереж. У дослідженні було використано методи сценарного моделювання, системного аналізу, структурно-функціонального порівняння та вивчення міжнародного досвіду. Було досліджено рівень втрат електроенергії в Україні станом на 2024 рік, який становив 18-19 % від загального обсягу виробленої енергії, причому близько 70 % цих втрат мали технічний характер. Було встановлено, що структура генерації електроенергії була сформована за участю атомної (55 %), теплової (24 %), гідро (9 %), сонячної (7 %) та вітрової (5 %) енергетики. Було проаналізовано, що часткове впровадження смарт-лічильників на рівні 50 % забезпечує зниження втрат на 25 %, тоді як повне охоплення розподільчої мережі може скоротити втрати до 45 %. Було узагальнено технічні характеристики інтелектуальних лічильників, які передбачають високочастотний збір даних з інтервалами 15 хвилин або однієї години, дистанційне передавання інформації в режимі реального часу через мобільні мережі або системи Power Line Communication (PLC), автоматичне виявлення аварійних ситуацій та несанкціонованого втручання. Було доведено, що інтеграція смарт-лічильників із системами управління енергоспоживанням дозволяє ефективно балансувати навантаження, знижувати пікові споживання й оптимізувати розподіл електроенергії. Також було узагальнено досвід США, ЄС і Китаю, який підтверджує доцільність широкомасштабного впровадження таких систем для зниження втрат і стимулювання розвитку розподіленої генерації. Отримані результати свідчать про перспективність застосування смарт-лічильників у цифровій трансформації української енергосистеми, що забезпечить її адаптивність, надійність та стійкість до нових викликів. Практична цінність дослідження полягає у розробці підходів до цифровізації обліку енергоспоживання в Україні, що може бути використано при модернізації енергомереж та формуванні стійкої розумної енергосистеми

Ключові слова: автоматизація обліку; управління ресурсами; цифрові технології; інтелектуальні системи; моніторинг споживання; ефективність споживання

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Viktor Duhanets*

Doctor of Pedagogical Sciences, Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
<https://orcid.org/0000-0002-3383-5907>

Pavlo Fedirko

PhD in Technical Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
<https://orcid.org/0000-0002-3724-8937>

Oleksandr Hovorov

PhD in Technical Sciences, Senior Researcher
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
<https://orcid.org/0000-0002-1645-1725>

Vitaliy Pukas

PhD in Technical Sciences, Associate Professor
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
<https://orcid.org/0000-0002-0083-7359>

Mykola Volynkin

Assistant
Higher Educational Institution "Podillia State University"
32316, 12 Shevchenko Str., Kamianets-Podilskyi, Ukraine
<https://orcid.org/0009-0006-4960-8537>

Modelling of dynamic characteristics of tractor systems to improve stability on uneven fields

Abstract. The study aimed to determine the impact of the centre of mass shift, the angle of inclination of the terrain and local disturbances on the spatial stability of the transport system, with the subsequent determination of its equilibrium limit modes. The methodology was based on a combination of theoretical modelling, adaptive control and multi-level validation in a changing environment. The critical vertical displacement of the hull was found to be up to 0.15 m at an 18° tilt due to the asymmetric passage of obstacles, which confirmed the need for accurate dynamics prediction. Stability analysis has established safe roll angles of 25-30° for Ukrainian black soil (friction coefficient 0.6-0.8). The uneven load and soil moisture content (20-30%) affected stability, requiring model calibration. Hybrid methods compensated for seat vibrations by adaptively controlling the damper. Adaptive ground contact improved traction on soft ground, while nonlinear predictive steering optimised the trajectory on slopes. The expediency of the geometry of the reference plane and the position of the centre of mass when developing algorithms for stabilising agricultural machinery, given the impact on stability in variable

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*Corresponding author



terrain, was established. Stochastic modelling of soil disturbances was used to predict the impact of random environmental changes on the trajectory and stability of the equipment. The proposed theoretical model is suitable for the design and dynamic hull control systems, especially for operation on slopes and complex geometries. The integration of sensor systems with models ensured adaptation to real-time conditions. The practical value of the results was to improve the safety of agricultural machinery and optimise its spatial orientation on slopes by process engineers and developers of active levelling systems when designing new generation machinery

Keywords: acceleration; grip coefficient; field testing; stabilisation; adaptive control

INTRODUCTION

Ensuring the stable operation of transport systems on uneven terrain is a critical condition for increasing the efficiency of agricultural machinery and reducing the risk of accidents. In many regions of Ukraine, soil cultivation takes place on difficult terrain with variable slopes, local elevations and depressions, which significantly affects the behaviour of machinery in the field. The current trend towards automation and the introduction of unmanned tractor systems also requires a deeper understanding of the patterns of loss of spatial stability in dynamic conditions. Therefore, the problem of predicting unstable modes of operation of machines on complex terrain is becoming increasingly relevant.

In the global scientific discourse, there have been studies on the stability of agricultural machinery on uneven surfaces, in particular in the context of safety, navigation efficiency and the introduction of adaptive stabilisation systems. Y. Chi *et al.* (2024) developed a numerical model that combined three-dimensional electromagnetic sensing with terrain parameters to predict the effect of undulating soil on signal propagation. Despite the specificity of the task (radar technology), the detailed development of the topographic profile and its integration into the simulation is valuable from a methodological point of view, especially for the construction of accurate terrain models and their further use in dynamic modelling of transport systems. W. Tong *et al.* (2024) addressed thermal modelling of the engine compartment of agricultural machinery based on temperature field measurements and airflow simulations. The study demonstrated the possibilities of digital simulation of complex internal processes in technical systems, which was methodologically useful for studying the stability of the hull under variable external loads.

The influence of complex topography on the behaviour of the system under conditions of surface changes was crucial in modelling unstable motion modes. In this context, the natural environment was considered a dynamic factor that changed the geometry of the reference plane. Q. Meng *et al.* (2025) proposed a multi-level model of forest evolution that addressed soil erosion and fire, combining different types of natural dynamics in a single simulation environment. This created the potential to apply similar approaches in technical sustainability analysis. Similarly, G.A. Ruetenik *et al.* (2023) optimised models of global landform evolution using ^{10}Be isotopic labelling of a naturally labelled isotope to estimate erosion rates and landscape changes. This approach improved the

accuracy of predicting unstable zones, which is critical for engineering modelling.

The spatial kinematics of the body and structural constraints played a crucial role in assessing the stability of the machines on slopes and bumps. Accurate modelling of the hull behaviour during rolling allowed the identification of limit states. Y.-J. Yang *et al.* (2024) implemented a dynamic model of a miniature crawler tractor to analyse the risk of rollover, considering the geometry, mass distribution, and slope of the terrain. The authors demonstrated the feasibility of body configuration and contact with the terrain when assessing stability. Similarly, A. Manoharan *et al.* (2024) proposed a two-level optimisation of trajectories on uneven terrain that addressed both the trajectory shape and ground interaction parameters through a refined wheel engagement model. These approaches demonstrated high efficiency for creating stabilisation algorithms, which was a relevant basis for developing models of spatial behaviour of vehicles in complex terrain.

In the Ukrainian scientific discourse, the problem of the stability of transport vehicles in difficult operating conditions remained insufficiently addressed. The limited access to modern test benches and models narrowed the possibilities of modelling critical modes. S. Hrushetskyi *et al.* (2024) proposed the concept of modular control of agricultural machinery, which allowed the machine to adapt to changes in load and conditions. Although the mechanism of spatial loss of balance was not highlighted, the authors' approach laid the groundwork for adaptive regulation of stability parameters. O.Y. Rebrov *et al.* (2023) developed a method for determining the optimal tyre size for wheeled tractors, which indirectly affected stability and traction on difficult terrain. Despite the absence of a full-body position model, their work reflected a desire for engineering detail in ground interaction, which is also relevant for tracked systems.

Despite the progress in the study of agricultural machinery stability, there is still a lack of comprehensive approaches to analysing the spatial dynamics of Tracked Robotic Vehicles (TRV) under conditions of variable surface geometry. Insufficient research has been done on how the centre of mass displacement, roll and pitch angles, as well as local disturbances, affect the stability of the body. This limits the ability to predict the critical modes of operation of machinery in terrain and complicates the formation of recommendations for stabilisation control, which is especially relevant in the context of the agricultural environment of Ukraine.

The study aimed to analyse the dynamic behaviour of a transport system on uneven terrain, incorporating the spatial position of the centre of mass, changes in the angle of inclination of the surface, and interaction with the supporting base to identify the limiting modes of stability loss. To achieve this goal, the effect of the centre of mass displacement on the critical loss of stability of the TRV was investigated. The objectives of the study were to determine the critical conditions for the loss of hull stability by analysing the displacement of the centre of mass, the occurrence of roll and the impact of local disturbances on the hull position; to analyse the effect of the terrain configuration and asymmetric loading on the stability of the movement to formulate technical recommendations for stabilising the hull position.

MATERIALS AND METHODS

The study was conducted between August 2024 and January 2025. The focus was on an integrated approach to assessing the sustainability of TRVs, addressing regional soil and terrain characteristics, and the practical limitations of agricultural and mining infrastructure. The study included 6 stages. At the first stage, three approaches to assessing TRV sustainability were systematised: analytical, experimental and simulation to identify the strengths and weaknesses of each approach, their suitability for real-world application in Ukraine and the potential for further integration. The choice of these approaches was justified by the need to strike a balance between accuracy (analytical), practical reliability (experimental) and flexibility in modelling complex situations (simulation). The combination of the results of the approaches created the basis for further modelling, control optimisation and validation of TRV behaviour. The second stage was to analyse the dynamics of TRVs on complex terrain, for which four main modelling methods were considered: multibody, concentrated parameter, kinematic and inverse dynamics. The choice of a particular approach was based on accuracy requirements, operating conditions and available computing resources.

At the third stage, hybrid adaptive control methods such as Adaptive Neuro-Fuzzy Inference System (ANFIS), Nonlinear Model Predictive Control (NMPC) and Active Disturbance Rejection Control (ADRC) were presented. These approaches allowed for to improvement of the accuracy of TRV control in variable soil conditions, including wet, compacted and uneven surfaces, and to provide adaptation to changing soil and terrain conditions, increasing modelling accuracy and control efficiency. Additionally, analytical methods based on classical physical models of equilibrium, dynamics and interaction with the ground and engineering criteria were considered to determine critical conditions for loss of stability, rollover moments, and traction capabilities of the equipment.

The fourth stage classified technical solutions for optimising tractor traction on difficult soil types. Three key approaches were considered: adaptive contact systems, flexible chassis and trajectory optimisation algorithms. These

solutions were chosen due to their ability to increase stability and efficiency in difficult soil and terrain conditions. This approach comprehensively covered both mechanical and algorithmic aspects of improving traction. In the fifth stage, we characterised the approaches to model validation: field, bench and virtual. Each method was chosen for its ability to provide different levels of accuracy, realism and control. The sixth stage systematised the methods of correction, adaptation and validation of TRV motion models in a changing environment. Methods were selected to improve the accuracy of the models by calibrating them on real data, identifying error limits, using parametric approximations, integrating them with sensor systems for real-time adaptation, and stochastic modelling of ground disturbances. This integrated approach addressed both physical and stochastic factors affecting the movement of the TRV, which was important for improving the reliability and accuracy of the models in real field conditions.

Based on the analysis of the advantages and limitations of existing approaches, a multilevel theoretical model of TRV dynamics is developed, considering the mechanics of movement, interaction with the ground, stochastic disturbances and validation. The model architecture provides for the integration of adaptive control methods (ANFIS, ADRC, NMPC) to compensate for dynamic uncertainty. Validation was carried out by comparing simulation results with field and bench test data. This approach ensured the accuracy of the description of TRV dynamics in complex terrain and created the basis for the development of intelligent control, navigation and stabilisation systems, which is also relevant for the agricultural conditions of Ukraine. The Zotero bibliographic manager was used to process the sources, which ensured the ordering of literature, the accuracy of references and the structured classification of materials. The use of data retrieval, analysis and synthesis methods were used to comprehensively investigate the methods of optimisation and validation of tractor systems' motion and stability models, which identified the key factors of influence of the variable environment and formulated sound recommendations to improve their efficiency.

RESULTS AND DISCUSSION

TRV driving on slopes and inclined surfaces is a key aspect of efficient operation in difficult terrain, including mountainous areas, agricultural land and areas with limited access. One of the main challenges in such conditions is the high risk of loss of stability, which can lead to rollover, slip or complete loss of control. A critical factor affecting the stability of TRVs is the effect of instantly changing dynamic forces. When driving on sloping terrain, complex combinations of gravitational, inertial and frictional forces arise, depending on the angle of inclination, speed and surface type. These forces change the load distribution between the pivot points, which can lead to a partial loss of traction or destabilisation. Another important factor is the position of the centre of mass. On an inclined surface, the centre of mass shifts relative to the support plane, which reduces the

safety margin and increases the likelihood of overturning, especially when the position of the body or attachments changes. Interaction with uneven ground creates additional difficulties. Pits, stones, loose or wet areas can cause the tracks to slip, get stuck or lose contact with the ground. This makes navigation difficult, especially in conditions of limited visibility or autonomous control (Zhou *et al.*, 2023).

Typical problems encountered when driving on slopes include vehicle overturning due to exceeding the permissible angle of inclination, slipping of the tires, especially when braking or making sharp turns, and loss of control when changing the load or speed. All these factors significantly complicate the operation of TRVs in real-world conditions and require the introduction of adaptive control

systems, algorithms for predicting machine behaviour, and improved design solutions to increase stability. Ensuring stable and safe movement of TRVs on difficult terrain requires an integrated approach that includes dynamic modelling, environmental assessment, and the development of intelligent control systems capable of adapting the machine's behaviour in real time to changing terrain conditions. Assessing the stability of TRVs on slopes and inclined surfaces is a critical step in ensuring their safe and efficient operation. There are three approaches to stability analysis: analytical, experimental, and simulation, each of which has its advantages and limitations and is used depending on the design stage, the level of available information, and accuracy requirements (Table 1).

Table 1. Basic approaches to analysing the stability of tracked vehicles on inclined surfaces

Method	Description	Advantages	Disadvantages	Application examples	Ukraine aspect
Analytical	Based on mathematical models that describe the balance of forces (gravitational, inertial, frictional) and moments that affect the stability of TRVs on slopes. Includes analysis of load distribution, centre of mass position and critical tilt angles to prevent tipping or slipping	High accuracy for idealised conditions. The ability to quickly predict critical parameters. Does not require physical testing, which reduces costs	Limited accuracy in difficult soil conditions. Does not cover stochastic factors (for example, changes in humidity). Needs simplification of complex nonlinear interactions	Analysis of the stability of a modular tractor with articulated steering on an uneven surface by modelling the distribution of forces. Estimation of critical tilt angles for a tractor-trailer system with consideration of inertial effects	A model of stability of a machine-tractor unit with a critical angle of inclination of up to 25° for Ukrainian black soil (friction coefficient 0.6-0.8) has been developed. The models are adapted to the various terrains of Ukraine, where the average slope angle is 15-20°
Experimental	They consist of field tests using load cells, inertial measuring units and video recording systems to assess the behaviour of TRVs on slopes. Can be used to validate theoretical models and identify real limitations	High data reliability due to real-world conditions. The ability to detect unforeseen factors. A framework for calibrating simulation models	The high cost and complexity of organising tests. Depending on the conditions of the test site. Limited reproducibility due to variable soil conditions	Experimental validation of tractor rollover stability on slopes with different soil conditions. Measuring the vertical dynamic characteristics of a tractor to assess the impact of uneven ground on stability	Tests on clay soils (humidity 20-30%), where the maximum deviation of the tractor's centre of mass was 0.15 m at an inclination of 18°, which confirmed theoretical calculations
Simulation	Use numerical modelling (e.g., Matrix Laboratory/Simulink, Automated Dynamic Analysis of Mechanical Systems, RecurDyn) to create virtual models of the TRV and the environment. Can be used to study different driving scenarios, including inclination angles, ground conditions and dynamic loads	The ability to test a wide range of conditions without risk to the equipment. High flexibility in parameter settings. Saves time and resources compared to experiments	Need for accurate input data and model calibration. High computational complexity for complex systems. Possible discrepancies with real-world conditions due to simplifications	Simulate TRV movement on slopes with varying ground conditions to optimise steering. Modelling tractor dynamics to analyse operator seat vibrations on uneven terrain	RecurDyn simulations have shown that for Ukrainian steppe conditions (traction coefficient 0.7), vibrations of the operator's seat are reduced by 12% when the machine-tractor unit suspension is optimised. The simulations covered terrain irregularities of up to 0.3 m, typical for typical agricultural conditions in Ukraine

Source: compiled by the authors based on B. Zhou *et al.* (2023), P.M. Kolahi & M. Nazemizadeh (2023), M. Belloni *et al.* (2023), H. Singh & M. Mehta (2024), G. Carabin *et al.* (2024), L. Duan *et al.* (2025), V. Nadykto *et al.* (2025)

Analytical, experimental, and simulation methods have been used to analyse the stability of tracked vehicles on sloping surfaces, each with unique advantages and limitations. Analytical methods are accurate for idealised

conditions, experimental methods provide reliability in real-world conditions, and simulation methods allow for flexible modelling but are dependent on data quality. In combination, they optimise the stability of machinery in

Ukrainian conditions with slope angles of 15–20° and unevenness of up to 0.3 m.

The choice of a particular model depends on the accuracy requirements of the analysis and the capabilities of computing resources. While multibody models provide the highest accuracy, they also require significant computational resources and simulation time. On the other hand, concentrated parameter models and kinematic models are less computationally demanding, but can be limited in

accuracy, especially on complex and variable terrain. To ensure stable and predictable behaviour of tracked vehicles on complex terrain, it is necessary to apply appropriate dynamics models that address both the physical properties of the system and variable terrain conditions. There are several approaches to modelling TRV movement, which differ in the level of detail, computational costs, and scope of application. Table 2 shows the types of models used to analyse the dynamics of tracked vehicles on uneven fields.

Table 2. Systematisation of approaches to modelling tractor dynamics on uneven ground

Approach	Description	Advantages	Disadvantages	Application examples
Multibody dynamics models	The most detailed approach that considers the complex rotational and translational relationships between chassis, suspension, articulated joints and tracked propulsion elements. The models describe the interaction of system components with all degrees of freedom, which allows analysing roll, pitch and rollover on uneven terrain	High accuracy in predicting dynamic behaviour. The ability to integrate complex subsystems (suspension, tracks). Suitable for stability analysis on difficult terrain	High computational complexity, requiring powerful resources. A need for careful calibration for specific soil and topographic conditions. Complex real-time implementation	Simulation of a semi-tracked tractor with articulated steering to assess stability on uneven surfaces, including analysis of the effect of obstacles on roll and pitch. Analysing the dynamics of an unmanned vehicle on uneven terrain to predict ground interaction and assess stability
Concentrated parameter models	Simplify the system to a set of masses, elasticities and damping elements. Used to analyse vertical dynamics, such as vibrations of the operator's seat, incorporating stochastic disturbances from uneven terrain	Easy implementation and low computational cost. It can be used in real time for adaptive control. Performance for comfort and vibration assessment	Limited geometric flexibility, which reduces accuracy for complex trajectories. Less detailed consideration of interaction with the soil. Unsuitable for difficult terrain with large gradients	Development of a damping system for a tractor seat that compensates for vibrations from bumps using a magnetorheological damper. Modelling tractor vertical vibrations to optimise operator comfort on uneven agricultural fields
Kinematic models	Address the trajectory of the movement without taking into account inertial effects. Used to analyse wheel or track rotation, steering angles and drive train speeds, suitable for SLAM systems	Low computational cost, which facilitates integration. Easy to integrate into navigation systems. Effective for predicting trajectory on flat surfaces	Does not address the effect of uneven ground. Limited accuracy on difficult terrain. Not suitable for stability or perturbation analysis	Planning the path of the tractor-trailer system in the garden environment to ensure precise navigation. Used in an autonomous driving system to determine the position of the tractor relative to landmarks on a flat field
Inverse dynamic models	Used to simulate the forces and moments required to execute a given trajectory or behaviour. Used for autonomous systems, considering terrain gradients and stability limitations	High accuracy for autonomous control. Integration with sensor systems (LiDAR, IMU). Efficiency for difficult terrain	Require careful optimisation and calibration. Dependence on the accuracy of sensor data. Complex real-time implementation	Trajectory planning for an autonomous vehicle on uneven terrain, incorporating terrain gradients and stability. Development of a control system for a tractor that ensures stable driving on slopes with variable ground conditions

Note: IMU – Inertial Measurement Unit; LiDAR – Light Detection and Ranging; SLAM – Simultaneous Localisation and Mapping

Source: compiled by the authors based on S. Han *et al.* (2024), Q. Li & H. Zhu (2024), D.K. Sah & M.F. Selekwa (2024), V. Bulgakov *et al.* (2024), W. Tao *et al.* (2025)

The systematisation of approaches to modelling tractor dynamics on uneven ground has shown that multibody models provide high accuracy for complex terrain, concentrated parameter models are effective for vibration analysis, kinematic models are suitable for navigation,

and inverse dynamic models are optimal for autonomous control. The integrated use of these methods was used to effectively solve stability and control problems in Ukrainian agricultural conditions. X. Gong *et al.* (2024) proposed an approach to planning vehicle trajectories on complex

surfaces in off-road conditions, based on a joint analysis of spatial and temporal characteristics to determine stability and optimise movement. The study analysed the creation of models that consider changes in terrain, with an emphasis on the development of trajectories important for vehicles operating on uneven surfaces. The proposed approach correlated with the current study, as both methods involved analysing the complex interactions of vehicle components, such as chassis, suspension, and track propulsion, to accurately predict movement in changing surface conditions. T. Sharma & Y. He (2024) studied the modelling, simulation, and optimisation of vibrations during tillage using an interactive active control system. The authors paid attention to the impact of terrain irregularities on the vibrations of agricultural machinery, in particular tractors, during tillage. The study demonstrated that reduction of vibration levels increased operator comfort

and improved productivity, which is consistent with the results of this study, both of which are aimed at optimising vibration characteristics and stabilising the operation of machinery, ensuring effective vibration management and minimising its negative impact.

Adaptive modelling techniques such as ANFIS, NMPC and ADRC are key in improving the stability and controllability of TRVs on uneven ground (Ismayilzada *et al.*, 2025). These methods combine classical physics models with machine learning algorithms to adapt to changing conditions such as uneven terrain, soil moisture or variable loads. They compensate for random disturbances, improve control accuracy, and contribute to the safety and efficiency of machinery in challenging agricultural and mining environments. A summary of these methods assessed their capabilities and limitations for practical use in modelling TRV dynamics (Table 3).

Table 3. Hybrid adaptive control methods for modelling and stabilising tractor movements on difficult terrain

Method	Description	Advantages	Disadvantages	Application examples
ANFIS	A hybrid method that combines neural networks and fuzzy logic to model nonlinear systems. Used to compensate for disturbances caused by uneven terrain by adaptively adjusting model parameters based on sensor data	Efficient compensation of nonlinear disturbances. Flexibility in adapting to changing conditions (soil moisture). High accuracy with sufficient data for training	Requires a large amount of verified data for training. The complexity of setting up fuzzy rules and network structure. Limited efficiency without quality sensor data	Compensates for vibrations of the tractor operator's seat on uneven agricultural fields employing adaptive damper control. Optimising tractor suspension performance to reduce the impact of stochastic disturbances from uneven terrain
NMPC	A predictive control method that uses a nonlinear model to predict system behaviour and optimise control actions in real time. Addresses the limitations of TRV stability and dynamics on slopes and bumps	High control accuracy on difficult terrain. Can account for constraints (e.g., slope angle, traction). Adaptation to changing conditions in real time	High computational complexity for real-time processing. Requires an accurate system model and high-quality data. The complexity of optimisation for nonlinear systems	Ensures truck stability on slopes by predicting the trajectory and adjusting the steering. Optimising the movement of an autonomous tractor on an uneven field, addressing changes in terrain gradients
ADRC	A method of active disturbance suppression that assesses and compensates for uncontrollable external influences (e.g., changes in soil structure or load) without a detailed system model. Used to increase the stability of the TRV	Does not require a detailed system model. Efficient compensation of unknown disturbances in real time. Ease of implementation compared to other adaptive methods	It depends on the quality of perturbation estimation. Limited accuracy in difficult nonlinear interactions. Requires careful adjustment of controller parameters	Compensates for the effect of changes in soil moisture on the traction of a crawler tractor when driving on uneven ground. Adapting tractor steering to load changes when towing a trailer on slopes

Source: compiled by the authors based on S. Han *et al.* (2024), G. Qi *et al.* (2025), L. Duan *et al.* (2025)

Hybrid adaptive methods (ANFIS, NMPC, ADRC) effectively compensated for nonlinear disturbances and ensured tractor stability on difficult terrain. Their application optimised steering in the conditions of changing soils and terrain typical for Ukraine but required high-quality data and computing resources. The combination of these methods helped to increase the productivity and safety of the machinery. The results of the study emphasised the importance of accurate models for assessing soil properties and adapting machinery to complex terrain, which was consistent with the study by H.A. Hamersma *et al.* (2024),

which demonstrated the importance of Unmanned Aerial Vehicle-based technologies for creating three-dimensional models of uneven surfaces and accurately predicting the interaction of machinery with the ground. Such modelling allowed for soil deformations and changes in traction, which were critical to the efficiency of vehicle movement. B. Puras *et al.* (2024) emphasised the role of virtual models (telehandler models) in improving the accuracy and adaptability of machinery to changing conditions. This supported the current study on the need to use sophisticated mathematical and virtual models to predict the

behaviour of vehicles on different types of ground, such as dry or highly compacted surfaces, where adaptive systems can provide optimal traction and stability.

Given the high computational complexity of modern technologies, as evidenced by both the authors' conclusions and this study, it is possible to argue that the effective implementation of such engineering solutions requires significant investment in the development, testing, and integration of sensor systems and digital (virtual) models. Adaptive technologies are accompanied by high costs for design, algorithmic software, and hardware implementation (Vintoniak, 2024). Thus, despite the potential benefits, the implementation of such systems is a financially and technically complex process that requires a comprehensive approach. Soil properties are decisive in ensuring the driving performance of tractor systems and TRVs on uneven surfaces. Parameters such as soil structure, moisture content, degree of compaction and the nature of the mechanical interaction between the propulsion system and the ground surface directly affect the traction coefficient, slope stability and manoeuvrability (Adamchuk et al., 2016). These factors are critical for the development of autonomous and operator control systems that ensure the stability and performance of vehicles in difficult terrain. The contact interaction between the crawler and the soil is characterised by complex nonlinear behaviour due to the

penetration of the tracks into the soil, the displacement of its particles and the emergence of three-dimensional soil resistance. The main factors that influence grip include the normal soil response, tangential shear forces and surface deformation. Mathematical models that describe these interactions are often based on Beckman's theory or empirical relationships that address the soil's modulus of deformation and bearing capacity (Dong et al., 2023). For example, nonlinear modelling with propulsion inertia can predict the behaviour of tractor-trailer systems on uneven terrain.

Soil physical properties, such as moisture content, particle size distribution and degree of compaction, are highly variable and depend on seasonal, climatic and agricultural factors (Bulgakov et al., 2017). Soil moisture affects soil cohesion and the angle of internal friction, which directly affects traction. Excessive moisture can reduce traction by reducing the friction between the tracks and the surface, while dry soil can have a higher load-bearing capacity but less plasticity (Hassan et al., 2017). Compaction of the soil caused by previous loads also changes its mechanical characteristics, which requires an adaptive modelling approach (Huseynov, 2024). These patterns are covered in models that use sensor data to assess soil conditions in real time. To compensate for the negative impact of soil conditions, modern TRVs use a number of engineering solutions aimed at increasing traction and stability (Table 4).

Table 4. Classification of technical solutions for optimising tractor traction on difficult soil types

Engineering solution	Description	Advantages	Disadvantages	Application examples
Wheel-step system	A mechanism that adapts the geometry of the vehicle's contact with the surface by dynamically adjusting the position of the wheels or tracks. It uses active or passive elements to change the contact area depending on ground irregularities, which ensures optimal load distribution	Improved traction on soft and uneven ground. Reduced sliding due to adaptive contact. Can be integrated with sensor systems for automatic adjustment	Complexity of design and high cost of implementation. Increased vehicle weight. The need for regular maintenance	Implementation of a wheel-step system in unmanned vehicles to increase traction on sandy or muddy ground. For use in crawler tractors to adapt to uneven terrain when driving on agricultural fields with vegetation residues
Yielding chassis	A flexible chassis design that can be used to adapt to changes in terrain by deforming or actively adjusting the suspension. Ensures constant contact of the tracks with the surface, reducing the risk of loss of traction on slopes	Increased stability on steep slopes and bumps. Reduced vibrations and stress on the structure. Improved operator comfort and system durability	The difficulty of designing flexible elements with sufficient strength. High development and implementation costs. Limited effectiveness on extremely uneven surfaces	Application in TRVs for driving on mountain slopes, where the flexible chassis compensates for elevation changes. For use in three-axle mining dump trucks to ensure stability on uneven terrain
Trajectory optimisation	Use of motion planning algorithms such as SLAM or NMPC to select optimal paths based on soil maps, terrain gradients and sensor data (LiDAR, IMU). Avoids low-grip areas and minimises slippage	High navigation accuracy in difficult conditions. Adaptation to changing ground conditions in real time. Reduced energy consumption and reduced risk of slipping	High computational complexity for real-time processing. Dependence on sensor data quality and map accuracy. Need for preliminary mapping of the area	Using SLAM to autonomously navigate a tractor in a horticultural environment with uneven terrain. Using NMPC to plan the path of a heavy vehicle on slopes with variable ground conditions

Source: compiled by the authors based on W.-H. Wang et al. (2023), L. Duan et al. (2025), X. Liu et al. (2025)

Basic engineering models and analytical formulas are also used to describe the conditions of rollover, traction loss and dynamic imbalance, which form the basis of

engineering models for the stability of tracked vehicles. These models can be used to quantify critical parameters, such as rollover angle or minimum traction coefficient, and

predict the behaviour of the vehicle in different conditions. Critical rollover angle (1):

$$\theta_{\text{crit}} = \arctan\left(\frac{b}{2h}\right), \quad (1)$$

where θ_{crit} – critical tipping angle; h – height of the machine's centre of mass above the support surface; b – width of the track or base of the machine, i.e., the distance between the track belts' support points; $\arctan$ – arctangent of the ratio, which gives the angle at which the gravity moment contributing to the tipping is equal to the stabilising moment.

The formula is based on a simplified analysis of the body's balance on an inclined plane and is used to estimate the critical angle of inclination at which a tracked vehicle can lose stability due to overturning. Static Stability Index (SSI) (2):

$$\text{SSI} = \frac{b}{2h}, \quad (2)$$

where SSI – dimensionless value that reflects the propensity to rollover, the higher the SSI value, the higher the rollover resistance.

Vertical dynamics of tracked vehicles (simplified mass-spring-damper model) (3):

$$m \times \ddot{z} + c \times \dot{z} + k \times z = F_{\text{drilling}}, \quad (3)$$

where m – reduced mass of the vehicle (including a tractor or robotic platform); c – damping coefficient, which characterises the ability of the system to absorb the energy of vibrations; k – stiffness of the suspension system, which characterises the ability of the system to deformation; z – vertical displacement of the mass; $\dot{z}$, $\ddot{z}$ – speed and acceleration of vertical displacement; F_{drilling} – external disturbing force caused by interaction of uneven terrain.

Overturning moment (moment causing instability) (4):

$$M_{\text{roll}} = m \times g \times h \times \sin(\theta), \quad (4)$$

where g – free fall acceleration; θ – slope angle.

Stabilising torque (anti-tipping torque) (5):

$$M_{\text{stabilising}} = \frac{m \times g \times b}{2}, \quad (5)$$

Minimum grip coefficient to avoid slipping (6):

$$\mu_{\text{min}} = \tan(\alpha), \quad (6)$$

where μ_{min} – minimum coefficient of adhesion to the surface required to avoid slipping; α – slope angle.

Formula for calculating traction force (7):

$$F_{\text{traction}} = \mu \times m \times g, \quad (7)$$

where F_{traction} – available traction, μ – actual coefficient of adhesion.

The efficiency of TRV movement is largely determined by the nature of interaction with the ground. One of the

most common approaches to modelling this interaction is the empirical model of M.G. Bekker (1962), which can be used to estimate the pressure exerted on the soil surface during deformation:

$$p = k_c \times \frac{1}{b} + k_\phi \times \left(\frac{z}{b}\right)^n, \quad (8)$$

where p – vertical pressure on the soil; k_c – soil compaction modulus; k_ϕ – soil shear resistance modulus; n – deformation nonlinearity index (dimensionless value).

Critical acceleration when tipping forward (9):

$$a_{\text{crit}} = \frac{g \times h}{L}, \quad (9)$$

where a_{crit} – critical acceleration at which the front wheels (or the front part of the track base) can leave the ground; g – free fall acceleration (9.81 m/s² – standard value for engineering calculations at sea level); L – length of the wheelbase or the base of the supports.

The main metrics for identifying error limits are the Mean Relative Error (MRE), Root Mean Square Error (RMSE), and Coefficient of Determination. MRE (10):

$$\text{MRE} = \frac{1}{n} \sum_{i=1}^n \left| \frac{y_i - \hat{y}_i}{y_i} \right| \times 100\%, \quad (10)$$

where y_i – actual value (measured); $\hat{y}_i$ – predicted value (model).

RMSE (11):

$$\text{RSME} = \sqrt{\frac{1}{n} \sum_{i=1}^n (y_i - \hat{y}_i)^2}. \quad (11).$$

Determination coefficient R (12):

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2}. \quad (12).$$

A Gaussian noise model was used to address the effect of microrelief on TRV vibrations:

$$F(t) = F_0 + \xi(t), \quad (13)$$

where $F(t)$ – instantaneous value of the disturbance force; F_0 – average (deterministic) value of the force; $\xi(t)$ – random time function whose value at each moment is a random variable with a normal (Gaussian) distribution.

To account for spatial variations in the coefficient of adhesion, a model with spatially correlated noise is used (14):

$$\mu(x, y) = \mu_0 + \delta(x, y), \quad (14)$$

where $\mu(x, y)$ – coefficient of adhesion at the point (x, y) of the surface; μ_0 – average value of the coefficient of adhesion; $\delta(x, y)$ – stationary Gaussian random field with zero mathematical expectation and spatial correlation structure.

Stochastic differential equations (15) are used to model the TRV response to stochastic disturbances:

$$dx = f(x, t) dt + g(x, t) dW_t, \quad (15)$$

where $f(x, t)$ – deterministic part of the dynamics (change of state per laws of mechanics); $g(x, t)$ – diffusion coefficient (noise effect); dW_t – stochastic differential of the Wiener process, which models independent normal random increments with zero mathematical expectation and variance proportional to dt .

Lagrange equation of the second kind (generalised form) (16):

$$\frac{d}{dt} \left(\frac{\partial L}{\partial \dot{q}_i} \right) - \frac{\partial L}{\partial q_i} = Q_i, \quad i = 1, \dots, n, \quad (16)$$

where q_i – generalised coordinates of the system (coordinates describing the position of the system in the configuration space); $\dot{q}_i$ – generalised velocities, time derivatives of coordinates; Q_i – generalised forces (or moments) that are not included in the potential energy, for example, friction forces, external forces acting in the direction of q_i .

The Newton-Euler equation (generalised vector form). Forward motion (17):

$$\sum \vec{F} = m\vec{a}. \quad (17)$$

Rotational movement (18):

$$\sum \vec{M} = \frac{d\vec{H}}{dt} = I\vec{\alpha} + \vec{\omega} \times (I\vec{\omega}), \quad (18)$$

where $\vec{M}$ – total moment of forces relative to the point of rotation; $\vec{H}$ – moment of quantity of motion (angular momentum); I – body inertia tensor; $\vec{\alpha}$ – angular acceleration; $\vec{\omega}$ – angular velocity.

For illustrative purposes, Figure 1 shows the distribution of forces acting on the TRV when travelling on an inclined surface and is used to explain the critical rollover angle model.

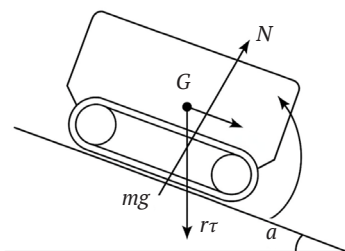


Figure 1. Spatial design scheme for determining overturning moments

Note: α – angle of inclination of the slope relative to the horizontal surface, which determines the steepness of the slope; G – point of the centre of mass of the machine, on which the distribution of forces depends; mg – force of gravity equal to the product of the mass of the machine (m) and the free fall acceleration ($g \approx 9.81 \text{ m/s}^2$), directed vertically downwards; N – normal force of the support reaction, which acts perpendicular to the surface of the slope and balances the vertical component of the weight; $r\tau$ – friction reaction directed along the slope, which prevents slipping due to adhesion to the surface

Source: compiled by the authors based on generalised provisions of classical mechanics of solid-state equilibrium, incorporating the configuration of tracked vehicles and typical situations of loss of stability on a relief surface

The stability of the TRV is significantly affected by the passage of local terrain irregularities, in particular, elevations and depressions that act asymmetrically on the undercarriage. In such conditions, the centre of mass is displaced and the roll angle φ is formed, which may exceed the permissible value. Figure 2 shows the conditional behaviour of the TRV when hitting a local obstacle, which visualises the change in the spatial orientation of the vehicle and the approach to the limit state of equilibrium.

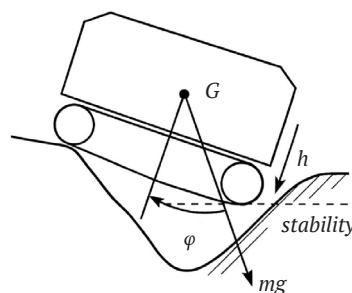


Figure 2. TRV limit position in case of loss of stability on the terrain

Note: stability – limit of the stable position of the TRV body, a conditional line beyond which the projection of the centre of mass (G) should exceed go, otherwise overturning occurs; mg – gravity, force of attraction equal to the product of the mass of the machine (m) and the acceleration of free fall ($g \approx 9.81 \text{ m/s}^2$), directed vertically downwards; h – the height to which the centre of gravity of the object is raised relative to the bottom of the slope; φ – angle of inclination of the trajectory or the angle between the vertical and the line connecting point G to a point on the slope. “Stability” conventionally reflects the ability of an object (tracked vehicle) to maintain balance and not topple over on a slope, which depends on the location of the centre of gravity (G), height (h), angle of inclination (φ) and gravity (mg)

Source: compiled by the authors based on generalised provisions of classical mechanics of solid-state equilibrium, incorporating the configuration of tracked vehicles and typical situations of loss of stability on a relief surface

To ensure the practical applicability of theoretical models of the dynamics of TRVs travelling on uneven ground, calibration and validation are necessary steps. Validation involves comparing the modelling results with experimental or simulation data to confirm their validity, while calibration adapts the models to real-world conditions by adjusting the parameters. These processes are critical for accurately predicting the behaviour of TRVs in variable soil and topographic conditions, which ensures safe and efficient operation (Table 5).

Field validation ensured reliability in real conditions, bench-top accuracy of isolated parameters, and virtual resource savings for testing complex scenarios. Their combined use increased the reliability of machine and tractor units adapted to the uneven terrain of Ukraine, which contributed to the accurate prediction of machine stability and dynamics. Experimental or virtual testing is not enough to

ensure the high accuracy of tractor movement model validation. An important step is also the use of model processing and adaptation methods that allow for variable operating conditions, reduce forecasting errors and increase the reliability of results. In this context, various approaches are

used, ranging from traditional parameter calibration to real-time integration of sensor data. Table 6 shows methods for improving modelling accuracy and adapting models to real-world conditions of agricultural machinery operation and examples of practical use.

Table 5. Characteristics of validation methods for models of dynamics and stability of machine-tractor units

Type	Description	Advantages	Disadvantages	Application examples
Field validation	Real-world field testing using load cells, IMUs, GPS and video recording systems to record driving, traction and stability parameters. Addresses stochastic factors such as soil moisture, uneven terrain and load changes	High reliability due to real-world conditions. Identification of unforeseen factors (crop residues). Basis for calibration of theoretical models	High cost and complexity of the organisation. Dependence on weather and soil conditions. Limited reproducibility due to environmental variability	Experimental validation of the tractor's rollover resistance on a training ground with different soil conditions (clay, sand), which confirmed the critical inclination angles of 25-30°. Field tests of a semi-tracked tractor to assess traction and load distribution on uneven surfaces
Bench validation	Tests in controlled laboratory conditions on rigs that simulate uneven terrain, vibrations or dynamic loads. Sensors are used to accurately measure individual parameters, such as vibrations or force distribution	High repeatability due to controlled conditions. Isolation of individual parameters (e.g., damping). Reduced risk to equipment compared to field tests	Inability to fully recreate the real environment. High cost of setting up and maintaining the stands. Limited applicability for complex scenarios	Bench testing of the vertical dynamic characteristics of a tractor to validate the operator seat vibration model. Validation of a magnetorheological tractor seat damper on a bench to compensate for vibrations from bumps
Virtual validation	Numerical modelling on platforms (Matrix Laboratory/Simulink, Automated Dynamic Analysis of Mechanical Systems, RecurDyn) to compare simulation results with experimental data. Can be used for testing of various scenarios (slope angles, soil conditions) without physical testing	Saving resources and time. The ability to test extreme conditions without risks. Flexibility in setting model parameters	Dependence on the quality of input data and calibration. High computational complexity for complex systems. Possible discrepancies with real conditions due to simplification	TRV simulation on slopes with variable ground conditions to validate stability and control models. Virtual validation of SLAM algorithms for tractor navigation in a garden environment with uneven terrain

Source: compiled by the authors based on M. Belloni *et al.* (2023), G. Carabin *et al.* (2024), Q. Li & H. Zhu (2024), W. Tao *et al.* (2025), L. Duan *et al.* (2025)

Table 6. Methods of correction, adaptation and validation of TRV motion models in a variable environment

Method	Characteristic	Advantages	Disadvantages	Application examples
Calibration of models	Iterative selection of model parameters (e.g., coefficient of adhesion, soil strain modulus) based on empirical data from field or bench tests to ensure that they match real-world conditions	Improving the accuracy of models by processing real data. Flexibility in parameter settings. Ability to adapt to changing conditions (humidity, terrain)	A need for a large amount of high-quality empirical data. High computational complexity for iterative fitting. Dependence on the accuracy of the measuring equipment	Calibration of a model of a magnetorheological tractor seat damper using vibration data for bump compensation. Selection of traction parameters for a semi-tracked tractor based on field tests
Identification of error limits	The process of determining the maximum permissible range of deviations between the calculated (model) and actual values of system parameters	Evaluating the model's compliance with real data can be used to determine its accuracy. Identification of errors in forecasts helps to improve the model. Comparing models with each other can be used to choose the most effective one	Collecting accurate data in the field is difficult because of moisture and uneven terrain. The need to recalibrate the model arises when conditions change, including soil type. The use of inaccurate input parameters leads to a decrease in the reliability of modelling results	Validation of the tractor navigation model in the garden, where error estimation refined the trajectory on different soils. Analysis of TRV stability on slopes, which helped to determine safe slope angles of 25-30°. Assessment of the traction characteristics of a half-track tractor for accurate predictions of possibility

Continued Table 1.

Method	Characteristic	Advantages	Disadvantages	Application examples
Parametric generalisation	Use of approximation structures (neural networks, regressions, ANFIS) to model non-linear relationships between model parameters and external factors such as temperature, soil moisture or vibrations	Coverage of complex factors. High flexibility and adaptability of the models. Ability to process stochastic data	A need for a large amount of data for training. Complexity of setting up approximation structures. Risk of model overtraining	Application of ANFIS for modelling tractor seat vibrations with consideration of stochastic irregularities. Use of neural networks to approximate the effect of soil moisture on TRV traction
Integration with sensor systems	Merges models with sensor data (LiDAR, IMU, pressure sensors) to adapt to real-time conditions. Enables dynamic adjustment of model parameters (trajectory, load distribution)	Adaptation to changing conditions in real time. Improved forecasting accuracy. Integration with autonomous control systems	High cost of sensor equipment. Dependence on the quality and frequency of sensor data. Difficulty in synchronising data with the model	Integration of LiDAR and SLAM to adapt the tractor's navigation model to uneven terrain in a horticultural environment. Using the IMU with NMPC to dynamically adjust the TRV path on slopes
Stochastic Differential Equation	Use of stochastic models (Gaussian noise, Stochastic Differential Equation, Monte Carlo, Pearl noise) to account for random changes in soil mechanical properties (density, moisture, microrelief) and their impact on TRV trajectory and vibrations	Incorporation of the randomness of the environment. The ability to model complex nonlinear effects. Flexibility in simulating different scenarios (pits, ledges, humidity)	High computational complexity (especially for Stochastic Differential Equations and Monte Carlo). A need for a large amount of data for noise calibration. Difficulty in forecasting for highly heterogeneous soils	Modelling the vibration response of a TRV to microrelief using Gaussian noise. Simulate the tractor's path on uneven ground to assess deviations. Analysing the effect of soil moisture on TRV traction using spatial noise

Source: compiled by the authors based on M.Z. Abdul Manaf *et al.* (2023), D. Dai *et al.* (2023), X. Ma *et al.* (2023)

The analysis of methods showed a variety of approaches to improving the accuracy and adaptability of TRV motion models. Calibration improved accuracy with high-quality data but was resource intensive. Error identification assessed reliability but depended on the data collection conditions. Parametric generalisation (neural networks, ANFIS) was effective for nonlinear relationships, but required large data sets. Integration with sensors (LiDAR, IMU) adapted the model in real time, although it was expensive and difficult to synchronise. Stochastic modelling addressed randomness but was computationally complex. The choice of method depended on the conditions, resources and goals, incorporating the balance of accuracy, adaptability and practicality. The root mean square error (Formula 11) reflects the average deviation between these values, providing a quantitative measure of discrepancy. The coefficient of determination (Formula 12) shows how well the model explains the variation in the data, with values closer to one indicating high accuracy. The influence of micro-terrain on vehicle behaviour is accounted for through a random oscillation model (Formula 13), which adds an element of randomness to the base force to simulate surface irregularities. Spatial variations in grip are modelled (Equation 14) through a baseline level of grip adjusted for spatial variations reflecting uneven terrain. Finally, stochastic effects affecting the system are described by equation (Equation 15), which combines predictable changes with random factors to analyse the vehicle's response to unpredictable conditions.

M. Ahmadian *et al.* (2024) addressed collision avoidance manoeuvres for heavy vehicles with multiple trailers.

The authors considered critical manoeuvres to ensure the safety and stability of such vehicles while driving in complex terrain. They proposed algorithms that consider various constraints and variable conditions, such as changes in load and terrain. The study emphasised the importance of accurate control algorithms to ensure driving stability in difficult conditions, which was directly consistent with the results of this study on the need to use adaptive systems to ensure traction and manoeuvrability on slopes and uneven surfaces. D.K. Sah & M.F. Selekwa (2024) examined the improvement of autonomous tractor-trailer driving using dynamic models. These models enabled real-time prediction of system behaviour, optimising movement using autonomous algorithms that adapt to changing terrain and soil conditions. The use of dynamic models to predict vehicle behaviour in real time was important for the development of autonomous control systems for tracked vehicles in difficult terrain. This was confirmed by the current results on the need to integrate such technologies to increase the traction and stability of vehicles on slopes.

Based on the analysis of the advantages and limitations of existing approaches, the concept of a generalised theoretical model of TRV dynamics that integrates key influence factors is formulated. The proposed multifactor integrated model is designed to comprehensively describe the behaviour of TRVs in conditions of complex terrain and heterogeneous soil. The modelling was carried out using multi-body or focused models that considered the characteristics of the suspension, mass-inertial parameters, and articulated frame elements. To describe the mechanics of motion, the Lagrange equations (Formula 16) (for

deriving the analytical model and validation) and Newton-Euler equations (Formula 17-18) (for flexible numerical implementation and accounting for rotational effects) were used, supplemented by stochastic disturbances to account for random effects. The model included parameterised dependencies of the grip and drag forces on soil properties, including density, moisture content and texture. Soil heterogeneity was modelled through stochastic effects on contact forces. The model included stochastic terrain disturbances, sensor (LiDAR, IMU) and actuator errors, load fluctuations (changes in cargo weight or soil moisture), and model imperfections. Adaptive control methods such as ANFIS, ADRC and NMPC are used to compensate for these factors. The model was validated by comparing it with real data obtained from field and bench tests. Validation involved estimating the errors between the simulation results and experimental data to ensure dynamic compliance and determine the permissible error limits.

The model had a multi-level organisation that provided a comprehensive consideration of physical, stochastic and experimental aspects of TRV motion. At the first level, the mechanics of the vehicle motion was implemented based on the Lagrange (Formula 16) or Newton-Euler (Formula 17-18) equations, supplemented by stochastic disturbances to simulate real dynamic impacts. The second level included modelling the interaction with the ground, based on empirical or semi-analytical relationships to describe the adhesion and drag forces. The third level included the consideration of random spatially distributed disturbances that simulated variability in relief and soil properties (moisture, density, microrelief). The fourth level served to validate the model by comparing the calculated data with the experimental results and estimating the errors, which was used to adapt the model parameters to improve its accuracy. Among the key advantages of the proposed approach is its comprehensiveness: the model simultaneously addresses TRV dynamics, soil interaction, stochastic disturbances and errors, which significantly increased the accuracy of simulations. The flexible structure of the model made it possible to adapt it to changing external conditions, including different terrain, soil types, and weather effects. This approach also facilitated the development of autonomous navigation, stabilisation and route planning systems. In addition, the framework was universal and could be applied to various types of mobile equipment, from agricultural to forestry and mining. At the same time, the model also had certain limitations, primarily high computational complexity due to the need to model multi-body dynamics and stochastic effects. Its effective operation required a large amount of high-quality experimental data for correct calibration. In addition, the reliability of the results depended heavily on the accuracy of the sensors and the reliability of the input data. Another challenge was the integration and configuration of adaptive control systems (ANFIS or NMPC), which required a high level of expertise and resources.

The results of the study showed that one of the key tasks in the design of TRVs was to ensure their stable

operation in complex and variable terrain. This can be achieved through the introduction of adaptive control systems that can address the changing characteristics of the terrain and soil cover. This correlates with the study by Z. Li *et al.* (2024), which considered the use of adaptive stabilisation algorithms in robotic tractors operating under conditions of increased uncertainty, in particular on uneven and dynamically changing surfaces. The model proposed in this paper included sensor feedback, which enabled real-time adjustment of movement parameters, ensuring stability during manoeuvring. Similarly, J.M. García *et al.* (2023) analysed the stability of vehicles when driving on slopes with uneven slopes and heterogeneous surface structures. The study emphasised the critical importance of parameters such as traction and weight balance, which determine manoeuvrability and safety in difficult terrain. Both studies confirmed the feasibility and necessity of using adaptive control systems to improve the efficiency and safety of TRVs, which was fully consistent with the results of this study. B. Wang *et al.* (2024) proposed an effective method for modelling and assessing the terrain of open pits, which included approaches to creating high-precision models of complex surfaces. Such models could be used to calculate the interaction of transport equipment with the ground in open pit mining. Incorporating the specific characteristics of the soil and terrain in the modelling allowed for a significant increase in the accuracy of predicting the stability of vehicle movement on slopes and uneven terrain. The current results of this study correlated with the approaches proposed by the authors and confirmed the importance of detailed digital terrain mapping for improving tracked vehicle control systems in difficult terrain.

Thus, the proposed concept of multifactorial theoretical modelling combines knowledge of mechanics, geotechnics, control theory and sensor systems, allowing not only to accurately describe the behaviour of TRVs in difficult conditions, but also providing a foundation for building smart, adaptive and predictive navigation and control systems of a new generation.

CONCLUSIONS

The study of approaches to analysing stability and modelling the dynamics of tracked vehicles on uneven surfaces systematised analysis methods, evaluated their effectiveness and developed a spatial model that described the loss of stability depending on the terrain, the position of the centre of mass and the type of disturbance. The analytical methods provided an accurate prediction of critical slope angles (up to 25-30° for chernozems with a friction coefficient of 0.6-0.8) but were limited in stochastic factors such as soil moisture. Experimental tests confirmed a vertical displacement of up to 0.15 m at an 18° inclination on clay soils, which highlighted the importance of accurate dynamics modelling, but high cost and dependence on testing conditions make it difficult to apply them widely. Simulation methods are effective in reducing vibrations by 12% by

optimising suspension and adapting to uneven terrain up to 0.3 m but require good quality input data.

Multibody models proved to be the most accurate for complex terrain, although their computational complexity limited their use in real time. Concentrated parameter models are effective for vibration analysis, and kinematic models are suitable for navigation on flat surfaces. Hybrid methods provide adaptability to nonlinear disturbances, which is critical for autonomous systems. Engineering solutions, such as the wheel-step system, increased the cross-country ability on soft ground through adaptive contact, and the flexible chassis reduced the risk of traction loss on slopes. Validation of the models through field tests (using IMU and GPS) and bench tests (to assess damping) confirmed their reliability, although the field tests proved to be sensitive to stochastic factors. The study was limited by the lack of field verification

of the model, complicated by the lack of application cases, insufficient infrastructure, high cost of technology, and limited access to empirical data in Ukraine. In the future, the model for predicting unstable modes of tracked vehicles can be improved by experimental validation, considering the dynamics of bogies, soil properties, and the introduction of multiphysics simulations with active stabilisers.

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CONFLICT OF INTEREST

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Віктор Дуганець

Доктор педагогічних наук, професор
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
<https://orcid.org/0000-0002-3383-5907>

Павло Федірко

Кандидат технічних наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
<https://orcid.org/0000-0002-3724-8937>

Олександр Говоров

Кандидат технічних наук, старший науковий співробітник
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
<https://orcid.org/0000-0002-1645-1725>

Віталій Пукас

Кандидат технічних наук, доцент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
<https://orcid.org/0000-0002-0083-7359>

Микола Волинкін

Асистент
Заклад вищої освіти «Подільський державний університет»
32316, вул. Шевченка, 12, м. Кам'янець-Подільський, Україна
<https://orcid.org/0009-0006-4960-8537>

**Моделювання динамічних характеристик тракторних систем
для підвищення стійкості при роботі на нерівних полях**

Анотація. Метою дослідження було з'ясування впливу зміщення центра мас, кута нахилу рельєфу та локальних збурень на просторову стійкість транспортної системи з подальшим визначенням граничних режимів її рівноваги. Методологія базувалась на поєднанні теоретичного моделювання, адаптивного керування та багаторівневої валідації в умовах змінного середовища. Було встановлено критичне вертикальне зміщення корпусу до 0,15 м при нахилі 18° через асиметричне проходження перешкод, що підтверджувало необхідність точного прогнозування динаміки. Аналіз стійкості встановив безпечні кути крену 25-30° для чорноземів України (коефіцієнт тертя 0,6-0,8). Нерівномірне навантаження й вологість ґрунту (20-30 %) впливало на стабільність, що вимагала калібрування моделей. Гібридні методи дозволили компенсувати вібрації сидіння шляхом адаптивного керування демпфером. Система адаптивного контакту з поверхнею покращила прохідність на м'яких ґрунтах, а нелінійне предиктивне керування оптимізувало траєкторію руху на схилах. Встановлено доцільність урахування геометрії опорної площини й положення центра мас при розробці алгоритмів стабілізації агротехніки з огляду на вплив на стійкість у змінному рельєфі. Стохастичне моделювання збурень ґрунту дозволило прогнозувати вплив випадкових змін середовища на траєкторію й стабільність техніки. Запропонована теоретична модель придатна для проектування та систем динамічного контролю корпусу, особливо для роботи на схилах і складній геометрії. Інтеграція сенсорних систем із моделями забезпечувала адаптацію до умов реального часу. Практична цінність результатів полягала у підвищенні безпеки роботи аграрної техніки та оптимізації її просторової орієнтації на схилах інженерами-технологами та розробниками систем активного вирівнювання під час проектування техніки нового покоління

Ключові слова: прискорення; коефіцієнт зчеплення; випробування в польових умовах; стабілізація; адаптивне керування

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Національний університет біоресурсів і природокористування України

03041, вул. Героїв Оборони, 15, м. Київ, Україна

Тел.: +38(044)-258-42-63

E-mail: info@technicalscience.com.ua

<https://technicalscience.com.ua/uk>