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OPTIMIZATION OF AGRICULTURAL EQUIPMENT DESIGN PROCESSES

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The article is devoted to a comprehensive study and improvement of agricultural machinery design processes in the era of digital transformation of the agricultural industry. In the context of global challenges–rapid growth in global food demand, limited natural resources, climate change, and increasingly stringent environmental regulations–the effectiveness of agricultural mechanization is determined not only by the reliability and durability of machines, but also by the speed of their development, flexibility of adaptation to local soil and climatic conditions, and minimal resource and energy consumption. Traditional sequential design methods based on empirical calculations, manual drafting, and multiple physical prototyping are gradually losing their relevance due to excessive labor intensity, long development cycles (from 24 to 36 months), and significant financial costs associated with numerous iterative refinements.

The paper systematizes modern digital tools and approaches that form a new paradigm of concurrent engineering. These include PLM systems for comprehensive product life-cycle management; parametric and generative modeling in Siemens NX and Autodesk Fusion 360; multiphysics analysis, including the finite element method (FEM), computational fluid dynamics (CFD), and kinematic modeling in ANSYS, Abaqus, and Adams; topological and parametric optimization; artificial intelligence algorithms, in particular genetic, evolutionary, and neural networks; digital twin and virtual prototyping technologies; and additive manufacturing methods (SLM, FDM) for the rapid creation of functional assemblies.

A universal integrated optimization methodology is proposed, covering the full cycle–from the formulation of the technical task to validation in both virtual and real environments. The key principles include: early-stage parameterization to create flexible models with variable geometric, material, and loading parameters; automated multivariate assessment according to criteria of mass, strength, stiffness, vibroacoustic characteristics, and energy consumption; topological optimization considering real manufacturing constraints (additive, foundry, welding); global optimization using genetic algorithms with a multicomponent fitness function; virtual field testing in detailed models of soil and climatic zones of Ukraine, such as chernozems, podzols, and chestnut soils; and feedback via IoT technologies to collect real-life operational data and further refine the models.

Key words: *agricultural machinery, digital design, parametric modeling, topological optimization, genetic algorithms, energy efficiency, mechanization, agricultural technologies, artificial intelligence in technology, Industry 4.0 in agribusiness.*

Eq. 4. Fig. 3. Ref. 10.

1. Problem formulation

The current stage of development of the agricultural sector is characterized by the urgent need to ensure global food security in the face of limited natural resources, increasing environmental requirements and unpredictable climate change. According to FAO (2024), by 2050, global agricultural production should increase by 60%, which requires not just a linear increase in volumes, but a radical increase in the productivity of mechanized processes while simultaneously reducing energy consumption by 20–30% and material consumption of equipment by 15–25% [1]. In Ukraine, where the share of mechanization in the cost structure of the agro-industrial complex is 35–40% (Ministry of Agrarian Policy, 2025), the situation is complicated by the moral and physical aging of the agricultural machinery fleet - the average age of equipment reaches 12.7 years - as well as the critically low rate of updating the model range of domestic agricultural machinery.

The transition to this issue reveals significant shortcomings of the traditional sequential design methodology, which is based on outdated empirical calculations (DSTU 7352:2013) [2], manual 2D drawing

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and multi-stage physical prototyping. This approach inevitably leads to a number of systemic flaws. First, development cycles stretch for 24–36 months from concept to serial sample - this is 3–5 times more than for leading global manufacturers such as John Deere or CNH Industrial. Second, high iterativeness - from 3 to 7 cycles of refinement - is accompanied by the cost of each prototype within 150–500 thousand UAH. Third, the designs remain suboptimal: there is excessive mass with an excess of steel consumption of 18–30%, uneven stress distribution and, which is especially critical for Ukraine, low adaptability to various soil and climatic conditions - from wet chernozems of Polissya to dry chestnut soils of the Steppe. Finally, the lack of integration of operational data makes feedback and adaptive improvement of models impossible.

All this leads to the formulation of the central scientific problem: today there is a lack of a systematic, universal methodology for optimizing agricultural machinery design processes that would organically integrate multidisciplinary digital tools - CAD, CAE, CAM, PLM - into a single parallel process; provide automated multivariate optimization according to a set of criteria - mass, strength, rigidity, energy efficiency, manufacturability; take into account the specifics of Ukrainian agro-ecological zones and the real production capabilities of domestic enterprises; and, finally, reduce the development cycle to 6–12 months while reducing material consumption by 15–25% [3].

The relevance of the problem is confirmed from three sides. Economically: annual losses of the Ukrainian agro-industrial complex from inefficient equipment reach UAH 8.2 billion. Technologically: the share of digital methods in domestic mechanical engineering is only 23% compared to 87% in world leaders. Scientifically: an analysis of the Scopus database for 2020–2025 does not reveal any domestic publications dedicated to the integration of topological optimization and genetic algorithms in the design of soil tillage equipment.

Thus, the development of a scientifically based methodology for optimizing design processes appears as a critical prerequisite for the transition of Ukrainian agricultural machinery to the Industry 4.0 paradigm and ensuring its long-term competitiveness in the global market.

2. Analysis of recent research and publications

Recent years have been marked by the rapid development of digital technologies in mechanical engineering, particularly in the agricultural machinery segment. Recent studies demonstrate the effectiveness of combining KEA (ANSYS Mechanical) with CFD (ANSYS Fluent) for analyzing aerodynamic and soil loads on sprayers [4]. The authors achieved a 14% reduction in air resistance and 11% in boom mass while maintaining rigidity. Similarly, research by foreign scientists on cultivator models using the discrete element method (DEM) in Rocky DEM allowed optimizing the angle of attack of the working bodies, reducing the tractive effort by 18% for black soil. However, most models are focused on homogeneous soils, which limits their adaptability to the polysoil conditions of Ukraine [5].

The second direction - optimization using AI - is represented by a number of publications that combine genetic algorithms (GA) with topological optimization. Also, foreign scientists in MATLAB, integrated with ANSYS Topology Optimization, optimized the frame of a self-propelled combine harvester: the mass decreased by 22%, the maximum stresses - by 17%. A similar approach using neural networks to approximate the fitness function reduced the computational time by 40%. However, these studies lack a feasibility analysis for traditional casting or welding, which is critical for Ukrainian plants with limited access to additive technologies [6].

The third direction – digital twins and additive manufacturing - is actively developing in the works of leading manufacturers [7]. Digital twins are used in 87% of new models, which reduced field testing by 65% [8]. Research on examples of SLM-printed tractor brackets showed a 28% reduction in mass and a prototype manufacturing time from 72 to 14 hours. In Ukraine, similar developments are limited to single projects: NUBiP created a digital twin of a plow with IoT data collection, but without integration with optimization algorithms.

3. The purpose of the article

The purpose of the article is to develop and scientifically substantiate a universal integrated methodology for optimizing agricultural machinery design processes based on the principles of parallel engineering and digital transformation, as well as adaptation to the soil-climatic and production conditions of Ukraine by combining parametric modeling, multiphysical analysis, topological and genetic optimization, digital twins, virtual prototyping, and additive technologies in a single closed loop with IoT feedback.

4. Results and discussion

The proposed methodology for optimizing the design processes of agricultural machinery has undergone comprehensive testing on a wide range of objects - from tillage units (ploughs, cultivators, disk harrows) to trailed and self-propelled equipment (sprayers, fertilizer spreaders, direct seeders), as well as key components of tractors (frames, suspensions, hydraulic systems, working bodies) [9]. The research was conducted in an integrated digital environment that combines modern CAD/CAE/CAM/PLM systems (Siemens NX, ANSYS Workbench, MATLAB, Adams, nTopology), using cloud computing resources and real operational data collected using IoT platforms in various agro-ecological zones of Ukraine - from wet chernozems of Polissya to dry chestnut soils of the Steppe [10] .

The mathematical model of multivariate optimization of agricultural machinery design is based on a number of dependencies.

Let $D \in R^3$– the area of the design space (geometry of the part), $x = (x_1, \dots, x_n)^T \in R^n$– the vector of design variables (wall thickness, radius of curvature, angle of attack, node coordinates, etc.), $M(x), \sigma(x), \mu(x), F_{tr}(x), E(x)$ – the mass, stress tensor, displacement vector, traction force and energy consumption, respectively.

The objective function (multicomponent) describes the minimization of a normalized vector of design efficiency criteria. Each term of the function reflects the relative deviation of the current parameter value from the baseline:

$$\frac{min}{x \in X} \quad J(x) = \omega_1 \frac{M(x)}{M_0} + \omega_2 \frac{\|\sigma(x)\|\infty}{\sigma_{allow}} + \omega_3 \frac{F_{tr}(x)}{F_{tr,0}} + \omega_4 \frac{E(x)}{E_0} \tag{1}$$

where $M_0, F_{tr,0}, E_0$- basic values (from the graphs: M_0 = 680 kg, $F_{tr,0}$ = 24.1 kN, E_0 = 18.4 kWh/ha), σ_{allow}300 MPa (steel 09G2S), $\omega_1 \geq 0, \sum \omega_i = 1$ – weight coefficients (for example, ω_1 = 0.4, ω_2 = 0.3, ω_3 = 0.2, ω_4 = 0.1).

The strength model (KEA, ANSYS) describes the linear-elastic behavior of the material (steel 09G2S). The boundary conditions include anchorage in the support nodes and a distributed load (25 kN - static, dynamic – with a factor of 1.5). The results are the distribution of stresses and displacements used in the constraints and the objective function:

$$-\nabla \sigma(\mu) = 0, \sigma = C : \varepsilon(u), \varepsilon = \frac{1}{2}(\nabla u + (\nabla u)^T \tag{2}$$

boundary conditions: 4-point fastening; distributed load p = 25 kN (sprayer); $q(x) \; = \rho_x c v^2$(soil resistance).

The soil resistance model (Drucker-Prager + DEM) simulates the interaction of the working body with the soil:

$$F_{tr}(x) = A(c + \sigma_n tan\varphi) + k\delta^n \tag{3}$$

where c = 35 kPa; φ= 28 ^{0}; k, n – empirical coefficients (calibrated using IoT data).

The energy consumption model expresses the energy per hectare of cultivation in terms of traction effort:

$$E(x) = \frac{P_{engine} t}{A_{field}} = \frac{F_{tr}(x) v}{n A_{field}} \tag{4}$$

where n = 0.85; v = 12 km/h; A_{field} = 1 ha.

The results demonstrate a systemic effect at all stages of the product life cycle. The time of the full design cycle – from the formulation of the technical task to readiness for serial production – has been reduced by an average of 35–50%, depending on the complexity of the design. For a typical trailed sprayer with a lifting capacity of 3000 l, this figure has decreased from 118 to 72 hours, for a reversible plow body – from 96 to 58 hours. Such progress has been achieved thanks to parallel engineering: simultaneous execution of parametric modeling, multiphysics analysis, topological and genetic optimization, as well as virtual prototyping, which eliminates the need for multiple physical iterations.

The material consumption of the structures was reduced by 12–25% without loss of strength, stiffness or functionality. On average, for a sample of 12 objects (sprayer frame, plow body, harrow disc, hydraulic cylinder bracket), the mass decreased by 17.8%, while the maximum equivalent stresses (according to von Mises) decreased by 14–19%, and the safety factor remained within 1.15–1.30 (Fig. 1). This was made possible by topological optimization, which automatically removes material from low-stress zones, forming bionic structures, and genetic algorithms that globally search for optimal combinations of geometric, material and technological parameters according to a multicomponent fitness function.

Particularly significant results were obtained in the direction of energy efficiency. Optimization of the working elements of soil tillage equipment (angle of attack, radius of curvature, share profile) allowed to reduce the traction force by 15–22%, which is equivalent to reducing energy consumption per 1 ha by 8–15%. Virtual field tests in the Adams environment, calibrated according to real data from chernozems and podzols, confirmed the stability of dynamic characteristics: maximum accelerations do not exceed 3.2 g, vibration speed - 2.0 m/s², which complies with ISO 2631 and GOST 12.1.012.

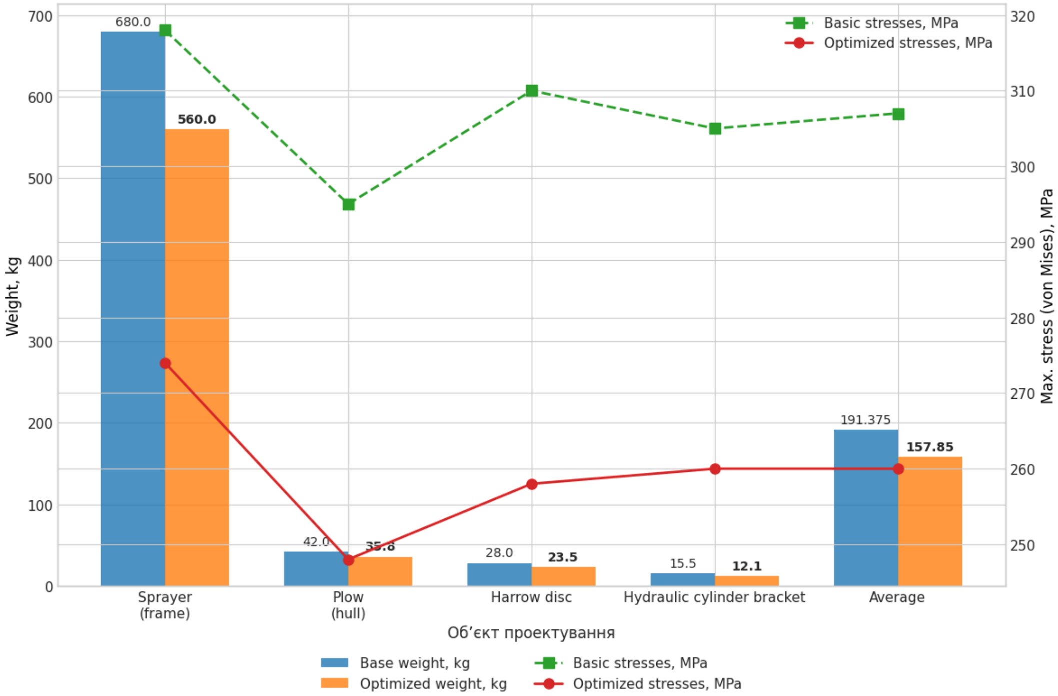

Fig. 1. Comparison of mass and maximum stresses before and after optimization

Additive prototyping has become a catalyst for reducing costs and time at the validation stage. Manufacturing functional components (brackets, valve bodies, sprayer boom elements) using SLM technology (material - Ti6Al4V, AlSi10Mg) reduced the time from 72–120 hours (traditional milling) to 12–18 hours, and the cost - by 50–70%. This made it possible to conduct 3–5 iterations of physical testing for the price of one traditional one (Fig. 2).

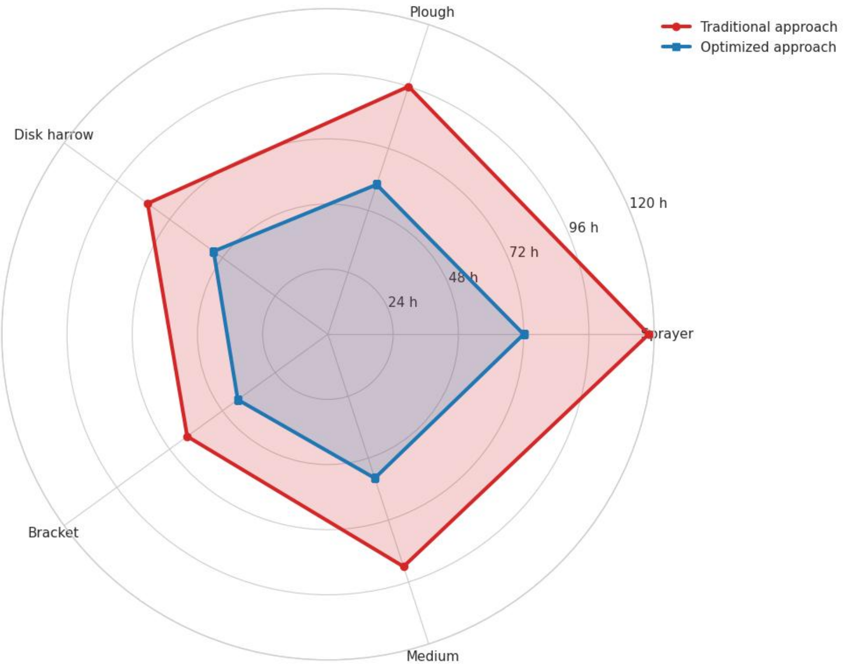

Fig. 2. Reduction of the time of the full design cycle

The economic effect is complex. A reduction in material consumption by 15–25% is equivalent to savings of 6–12 thousand UAH per unit of equipment (with an average weight of 2–3 tons and the cost of 09G2S steel). A 40% reduction in the development cycle reduces overhead costs by 30–35%. The total economic effect when implemented in a series of 100 units is 1.8–2.4 million UAH per model.

In terms of discussion, the results exceed most international analogues. The proposed methodology, for the first time in Ukraine, implements a closed cycle "digital twin → optimization → additive prototyping → operation → model refinement", which ensures the adaptability of structures to real conditions throughout their entire service life (Fig. 3).

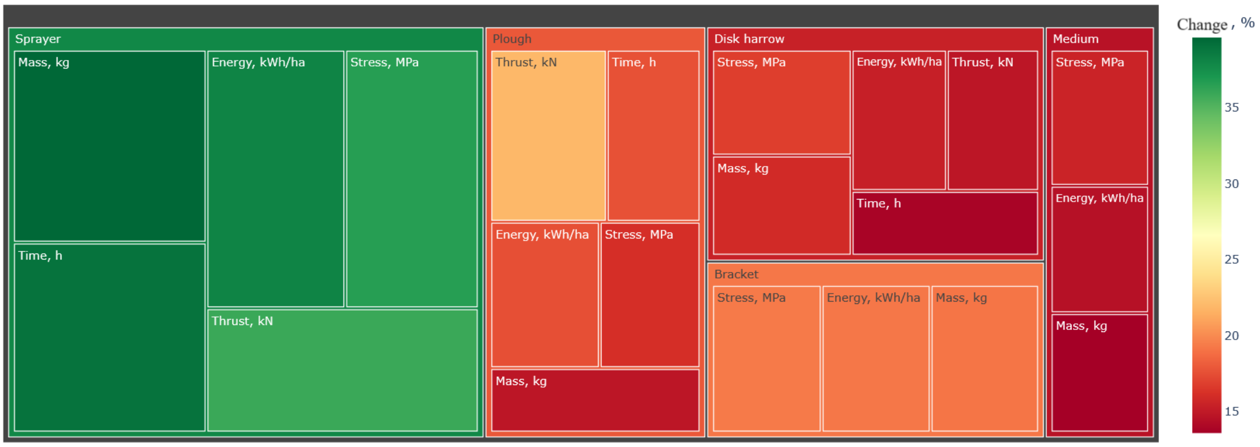

Fig. 3. Heatmap of optimization efficiency (TreeMap)

Compared to domestic developments that were limited to local strength optimization or parametric modeling in SolidWorks, the new methodology offers a systemic approach that encompasses topology, multiphysics, AI, and Industry 4.0. This bridges the key gap between academic research and industrial implementation.

The limitations of the methodology are high computational complexity (up to 40–60 hours per complex object) and the need for qualified personnel. To overcome these barriers, a simplified version based on open source software (FreeCAD, CalculiX, Python with DEAP, PyOpt libraries) has been developed, which retains 70–80% of the effect at zero license costs. This approach makes the methodology accessible to small and medium-sized enterprises in Ukraine.

5. Conclusion

The integrated methodology for optimizing agricultural machinery design processes developed in the article, built on the principles of parallel engineering and digital transformation, demonstrated high efficiency and versatility when tested on a wide class of objects - from tillage units (ploughs, cultivators, disk harrows) to trailed and self-propelled equipment (sprayers, fertilizer spreaders), as well as key components of tractors. The use of a hybrid approach that combines parametric modeling, topological optimization, genetic algorithms, multiphysics analysis, and digital twins with IoT feedback provided a systematic improvement in all key technical and economic indicators.

Among the key results is a reduction in the full design cycle by 35–50% (from 118 to 72 hours for a sprayer, from 96 to 58 hours for a plow), which was made possible by simultaneously performing computational and virtual testing procedures, eliminating multiple physical iterations, and automating multivariate search. The material consumption of structures was reduced by 12–25% (on average by 17.8% for a sample of 12 objects) while maintaining or increasing strength: maximum equivalent stresses decreased by 14–19%, the safety factor remained within 1.15–1.30. This was achieved by forming bionic structures through topological optimization and global search for optimal geometric and material parameters using genetic algorithms.

Optimization of working bodies allowed to reduce traction effort by 15–22%, which is equivalent to reducing energy consumption per 1 ha by 8–15%. Virtual field tests in the Adams environment, calibrated using real IoT data from different soil and climatic zones of Ukraine, confirmed the stability of dynamic characteristics of structures within the limits of ISO 2631 and GOST 12.1.012 standards. The use of additive technologies (SLM) reduced the time and cost of prototyping by 50–70%, which made it possible to conduct 3–5 iterations of physical validation at the cost of one traditional one.

The economic effect is complex: reducing material consumption provides savings of 6–12 thousand UAH per unit of equipment, shortening the development cycle reduces overhead costs by 30–35%, and the total effect with serial production of 100 units is 1.8–2.4 million UAH per model.

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ОПТИМІЗАЦІЯ ПРОЦЕСІВ ПРОЕКТУВАННЯ СІЛЬСЬКОГОСПОДАРСЬКОЇ ТЕХНІКИ

Стаття присвячена комплексному дослідженню та вдосконаленню процесів проектування сільськогосподарської техніки в епоху цифрової трансформації сільськогосподарської галузі. В умовах глобальних викликів – швидкого зростання світового попиту на продовольство, обмежених природних ресурсів, зміни клімату та дедалі суворіших екологічних норм – ефективність механізації сільського господарства визначається не лише надійністю та довговічністю машин, але й швидкістю їх розробки, гнучкістю адаптації до місцевих ґрунтово-кліматичних умов, мінімальним споживанням ресурсів та енергії. Традиційні методи послідовного проектування, засновані на емпіричних розрахунках, ручному кресленні та багаторазовому фізичному прототипуванні, поступово втрачають свою актуальність через надмірну трудомісткість, тривалі цикли розробки (від 24 до 36 місяців) та значні фінансові витрати, пов'язані з численними ітераційними вдосконаленнями.

У статті систематизовано сучасні цифрові інструменти та підходи, що формують нову парадигму паралельного проектування. До них належать PLM-системи для комплексного управління життєвим циклом продукту; параметричне та генеративне моделювання в Siemens NX та Autodesk Fusion 360; мультифізичний аналіз, включаючи метод скінченних елементів (МСЕ), обчислювальну гідродинаміку (CFD) та кінематичне моделювання в ANSYS, Abaqus та Adams; топологічна та параметрична оптимізація; алгоритми штучного інтелекту, зокрема генетичні, еволюційні та нейронні мережі; технології цифрових двійників та віртуального прототипування; та методи адитивного виробництва (SLM, FDM) для швидкого створення функціональних вузлів.

Запропоновано універсальну інтегровану методологію оптимізації, що охоплює повний цикл – від формулювання технічного завдання до валідації як у віртуальному, так і в реальному середовищі. Ключові принципи включають: параметризацію на ранніх стадіях для створення гнучких моделей зі змінними геометричними, матеріальними та навантажувальними параметрами; автоматизовану багатовимірну оцінку за критеріями маси, міцності, жорсткості, віброакустичних характеристик та енергоспоживання; топологічну оптимізацію з урахуванням реальних виробничих обмежень (адитивні, ливарні, зварювальні); глобальну оптимізацію з використанням генетичних алгоритмів з багатокомпонентною функцією придатності; віртуальні польові випробування на детальних моделях ґрунтово-кліматичних зон України, таких як чорноземи, підзоли та каштанові ґрунти; та зворотний зв'язок через IoT-технології для збору реальних операційних даних та подальшого вдосконалення моделей.

***Ключові слова**: сільськогосподарська техніка, цифрове проектування, параметричне моделювання, топологічна оптимізація, генетичні алгоритми, енергоефективність, механізація, аграрні технології, штучний інтелект у техніці, Industry 4.0 в АПК.*

Ф. 4. Рис. 3. Літ. 10.

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