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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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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 CO_2 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; Boresi & 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).

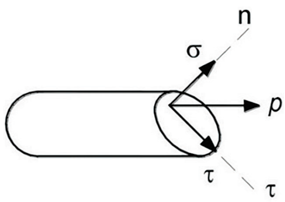

Figure 1. Stress and strain distribution diagram in a structural element of the cylindrical part of a mounted seed drill frame

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, ρ – 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).

Trailed 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. Raheman & 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):

$$\sigma = E \times (\varepsilon - \varepsilon 0), \tag{6}$$

where: E – modulus of elasticity of the material, ε0 – 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 CO_2 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 CO_2 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 N_2O emissions, requiring further study. The use of biogas and solar energy in agricultural systems incorporating optimised equipment reduced ecological pressure, supporting sustainability (Kiehbadroudinezhad *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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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 пальне й обслуговування, екологічній стійкості шляхом зменшення викидів, а також покращенню умов праці операторів завдяки зниженню вібраційних навантажень. Результати дослідження можуть бути використані при проєктуванні 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