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Review
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Use of finite element method in agricultural machinery and application examples*

Sonlu elemanlar metodunun tarım makinelerindeki kullanımı ve uygulama örnekleri

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ABSTRACT

Finite Element Method (FEM) is one of the engineering analysis methods that was developed to create mathematical solutions and has become widespread with the advent of computers. FEM is a method that can simulate the changes that different physical effects on material through numerical analysis. With the increase in computer processing speed and capacity, more effective and accurate solutions can be achieved. Agricultural machinery works in diverse environments under dynamic loads under forces acting in multiple directions. In designed machines, analyses can be performed without prototypes or physical manufacturing, thanks to simulations created with computer software. In this study, research on agricultural machinery is examined and reviewed. In the studies carried out with agricultural machinery, the strength of tillage machines, the effect of soil-share interaction on soil profile and share deformation, the strength of the harvester and the fertilizer scraper, chassis strength of tractor protective equipment and agricultural carts, strength of fertilizer mixing shaft and ergonomic solutions are presented. Various modelling and simulation approaches have been employed in these studies. By analyzing different operational conditions, results closer to real experimental data have been obtained using the Finite Element Method in agricultural machinery.

Keywords: Computer aided design/engineering, simulation, strength, stress analysis

ÖZ

Matematiksel çözümlemeler oluşturmak için geliştirilen ve bilgisayarların ortaya çıkmasıyla yaygınlaşan mühendislik analiz yöntemlerinden biri de Sonlu Elemanlar Metodu (SEM)'dur. SEM, sayısal analiz yoluyla malzeme üzerindeki farklı fiziksel etkilerin değişimlerini simüle edebilen bir yöntemdir. Bilgisayarların işlem hızı ve kapasitesinin artmasıyla daha etkili ve doğru çözümlere ulaşılabilmektedir. Tarım makineleri, birden fazla yönde etki eden kuvvetler altında dinamik yükler altında çeşitli ortamlarda çalışır. Tasarlanmış makinelerde, bilgisayar yazılımlarıyla oluşturulan simülasyonlar sayesinde prototip veya fiziksel üretim olmadan analizler yapılabilir. Bu çalışmada tarım makineleri üzerine yapılan araştırmalar incelenmekte ve gözden geçirilmektedir. Tarım makinaları ile yapılan çalışmalarda; toprak işleme makinaları dayanımı, toprak-uç demiri etkileşiminin toprak profiline etkisi ve uç demirinde oluşan deformasyonu, hasat makinasının ve gübre sıyırıcının dayanımı, traktör koruyucu ekipmanları ve tarım arabalarının şasi dayanımları, gübre karıştırma milinin dayanımı ve ergonomik çözümlemeler bulunmaktadır. Bu çalışmalarda çeşitli modelleme ve simülasyon yaklaşımları kullanılmıştır. Tarım makinalarında Sonlu Elemanlar Yöntemi kullanılarak farklı işletme koşulları analiz edilerek gerçek deneysel verilere daha yakın sonuçlar elde edilmiştir.

Anahtar sözcükler: Bilgisayar destekli tasarım/mühendislik, simülasyon, mukavemet, gerilme analizi

INTRODUCTION

The finite element method (FEM) is a numerical analysis technique widely used in solving complex physical problems, especially in engineering. FEM analyzes complex systems by breaking them down into finite elements, called smaller, simpler parts. FEM works based on the principle of analyzing individual elements to predict the overall behavior of a system (Güler & Şen, 2015). Each element is modelled with mathematical tools, such as differential equations and integral equations which describe the overall behavior of the system. These equations define the relationship between elements and contribute to the overall system behavior. FEM solves these equations and determines the results using linear algebra and numerical analysis methods. In this way, engineers can precisely predict the behavior of structures and systems. These elements, usually triangular or quadrilateral, are defined by simple equations that represent the general behavior of the system. This approach allows for the modelling of complex geometric shapes and loading conditions. FEM can be used in static, dynamic, thermal, and fluid analysis (Atıcı et al., 1996; Zeytinoğlu, 2005; Çelik et al., 2007; Kaplanlıoğlu & Gemalmayan, 2015; Yıldırım & Esim, 2019; Ünal et al., 2022; Baidhe & Clementson, 2024). This method allows engineers and designers to study the behavior of structures, materials, and physical systems in detail (Özden & Gökçe, 2023). It also allows for virtual simulation and analysis of various components and systems, helping engineers to optimize the performance and reliability of agricultural equipment before physical prototyping (Bamberg, 2000; Engelhardt et al., 2019).

The origins of FEM date back to the 1940s. This method, which was first developed for use in the fields of aeronautical engineering and aerospace engineering, has spread to other engineering disciplines over time. It was first used in aerospace engineering in the 1950s and was adopted by companies such as Boeing, Bell Aerospace, and Rolls Royce. The foundational paper was published by Turner et al. in 1956 (Güler & Şen, 2015). With the advances in computer technology, FEM has become a powerful tool for more complex and precise analyses. Today, it is considered an indispensable tool in engineering design and analysis. Beyond these fields, thanks to developing technology, it has started to be used in the field of agricultural engineering, such as soil-machine and machine-machine interaction, and even in medical surgical procedures outside of engineering fields (Çelik et al., 2007; Kibar & Öztürk, 2012; Kaplanlıoğlu & Gemalmayan, 2015; Altuntaş et al., 2018).

The advantages of FEM in the analysis include the ability to handle complex geometries and loading conditions, facilitating design optimization and improvements that save cost and time, and the reducing or eliminating the need for physical prototyping. However, the disadvantages include high computational costs, complexity of modelling and analysis processes, the need for accurate boundary conditions and material properties to obtain accurate results, and significant hardware and software requirements (Kibar & Öztürk, 2012; Güler & Şen, 2015; Yıldırım & Esim, 2019; Ünal et al., 2022).

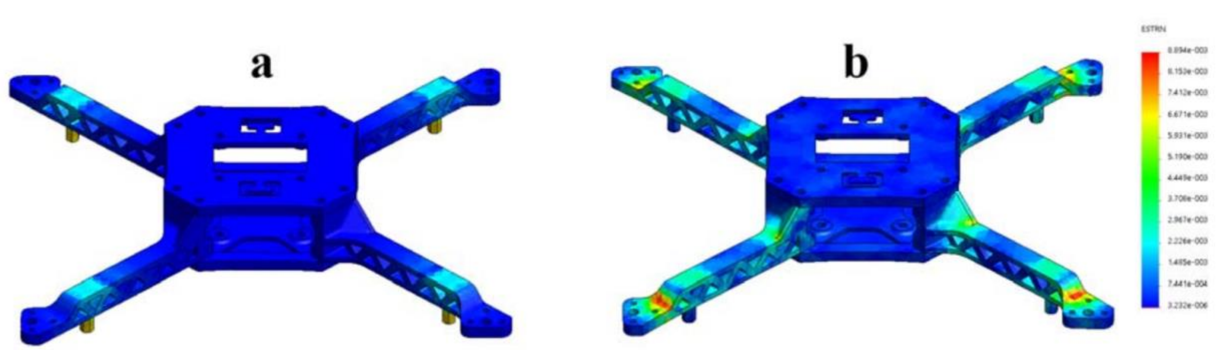

Figure 1. Example of the use of FEM in the UAV body (Martinetti et al., 2018).

Şekil 1. *İHA gövdesinde SEM kullanımı örneği* (Martinetti et al., 2018).

Agriculture involves the cultivation of soil for crop production and the rearing of livestock to supply food and other essential products for human and animal needs. Throughout history, agricultural activities have evolved alongside human civilization, driving rapid mechanization and the increasing integration of advanced technologies to meet growing demands. Agricultural machinery plays a critical role in improving efficiency and productivity in modern agricultural practices. Tractors, combines, seeders, and other agricultural machinery streamline production processes, enabling farmers to increase yields while reducing labor and time requirements. The durability and efficiency of these machines are vital to the success of agricultural activities. Therefore, the design and analysis of agricultural machinery is an important field of study for engineers (Kibar & Öztürk, 2012; Engelhardt et al., 2019; Çelik et al., 2020; Schramm et al., 2020; Zhu et al., 2023).

FEM is used to determine the interactions between agricultural machinery and soil, as well as soil machine interactions. It is also used for post-harvest processing of agricultural products. It is also employed for post-harvest processing of agricultural products such as grapefruit, kiwi, watermelon, tomato, and onion, during and after harvest are included in the literature (Ashtiani et al, 2019; Li et al., 2020; Zulkifli et al., 2020; Rashvand et al., 2022). Additionally, the finite element method can also be used to simulate the interaction of milking machines with dairy animals (Değirmencioğlu et al., 2005).

The use of unmanned aerial vehicles (UAVs) has entered our lives with Agriculture 4.0 and smart agricultural applications, which have emerged due to technological developments, and are constantly advancing. Many researchers in our country and around the world are working on the use of UAVs in various agricultural applications. Simulations created with FEM are used to determine and improve the safety coefficients of the materials used in UAV manufacturing and to optimize their weight (Martinetti et al., 2018; Singh et al., 2020; Zhang et al., 2021; Beyaz, 2023). Figure 1 shows the stress distributions obtained using FEM in the UAV body.

Use of Finite Element Method

The applications of FEM in agricultural machinery include structural analysis, strength and stress evaluation, as well as optimization and design improvements. This study reviews various FEM applications in agricultural machinery design, emphasizing both its benefits and limitations in addressing sector-specific challenges.

FEM is used to analyze the durability and strength of the structural components of agricultural machinery. The behavior of load-bearing roofs and frames of agricultural machinery under various loading conditions can be analyzed with FEM. These analyses can provide realistic values for optimizing the design of load-bearing roofs and frames and calculating durability values. It can offer specific data for the assessment of the long-term durability and reliability of agricultural machinery. This is especially important to ensure that machines operate reliably under extreme loads or harsh operating conditions. FEM analyses can guide preventive maintenance and improvement efforts by identifying potential weak points. It can also be used for design improvements and optimizations of agricultural machinery. By optimizing material usage, designers and manufacturers can reduce costs and increase machine performance thanks to this method. FEM can be applied to optimize the parts of seeders, to improve seed usage, prevent waste by adhering to specified norms, and to increase planting precision.

There are certain stages to follow during FEM analysis. These stages can be divided into three phases: preprocessor, solution, and postprocessor (Kibar & Öztürk, 2012). The first step, before these stages, is to model the object to be simulated in three dimensions. Many software packages are available for 3D modelling. After modelling, the next step is preprocessing. The first task here is to determine the physical and mechanical properties of the material (material type, modulus of elasticity, Poisson's ratio, unit weight, etc.). The second task is meshing. The meshing, which is critical accuracy of the analysis (Demir, 1999; Kibar & Öztürk, 2012; Kaplanlıoğlu & Gemalmayan, 2015). The quality of the mesh — including geometric data, physical properties, and number of nodes affects closeness of results to reality. A more appropriately mash structure yields results that closer to real conditions. The next stage is to be performed. Load and boundary conditions set during this phase. The software distributes the loads to the node based on boundary conditions and performs calculations accordingly. The final stage is the postprocessor, where the results are obtained and interpreted. Results can be presented as tables, figures, and drawings (Kibar & Öztürk, 2012; Kaplanlıoğlu & Gemalmayan, 2015). Figure 2 illustrates the formation of the mesh stage in FEM demonstrating the network creation process in grapefruit as an example.

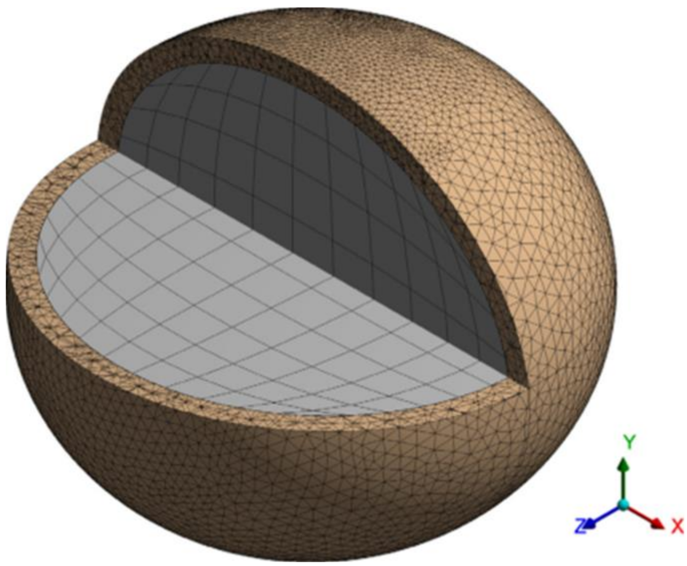

Figure 2. Meshing process (Ashtiani et al., 2019).

Şekil 2. *Ağ oluşturma süreci.*

Finite Element Method Application Examples in Agricultural Machinery

The finite element method plays a crucial role in terms of the analysis of engineering activities. There are many studies presented in the literature on the design and optimization of agricultural machinery. In addition, studies to determine soil-machine interaction are intensive. In these studies, FEM was combined with the Discrete Element Method (DEM) to enhance the accuracy and sensitivity of the analyses (Üçgül, 2019; Li et al., 2020; Guo et al., 2021; Zhu et al., 2023; Baidhe & Clementson, 2024).

The application of the finite element method has also been observed in the analysis of the interaction between agricultural implements and soil. It has also been instrumental in understanding the complex interactions between agricultural machinery and the working environment. Agricultural machinery frequently operates under harsh conditions, including rough terrain, high humidity, and exposure to corrosive substances, leading to premature wear and component failure. By modelling the mechanics between tillage machines, such as plows or cultivators, and soil, researchers are able to model the forces that the machine is subjected to during operation, the stresses that occur, and the deformation. The data collected using modelling can be used to design agricultural machinery with the required durability and increased efficiency (Chiorescu et al., 2017). Figure 3 presents FEM-based analysis examples in agricultural machinery.

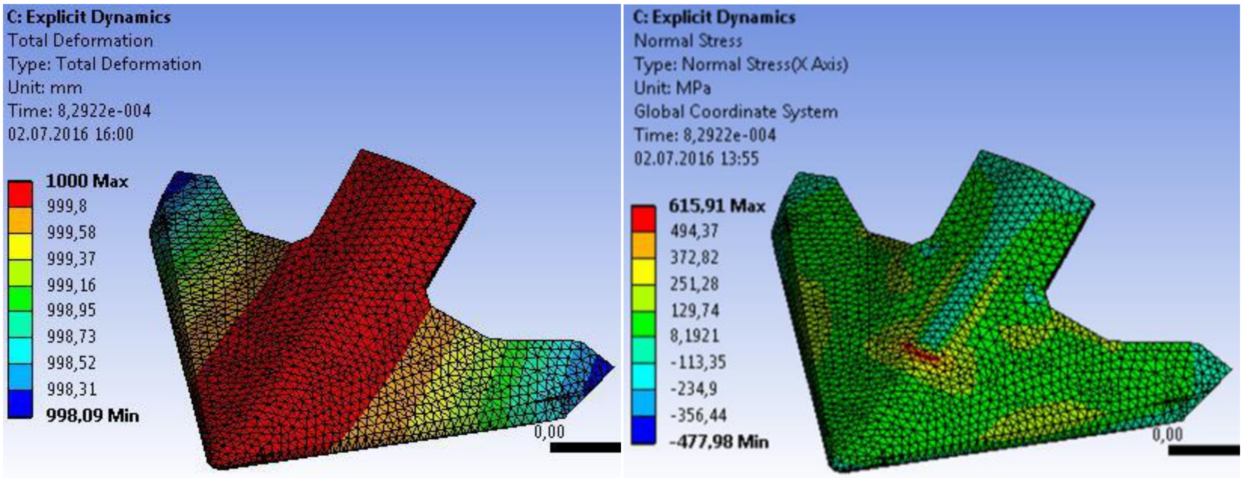

Figure 3. Examples of FEM analyzes for cultivator share (Chiorescu et al., 2016).

Şekil 3. *Kültivatör uç demiri için SEM analiz örnekleri.*

A major area where the finite element method has proven useful is its ability to enable the rapid design of agricultural machinery (Bamberg, 2000). FEM allows designers to virtually simulate and analyze machine components before physical prototyping (Vanderplaats, 1989; Huang et al., 2018). This creates advantages in terms of time and cost, especially in the agricultural sector where prototyping can be time-consuming and expensive. The analysis and refinement via simulations enables designers to specify and modify various design parameters and evaluate their impact on performance without need for extensive physical testing. Researchers use FEM analysis to determine the optimal parameters for designing a threshing roller for high-moisture corn, increasing efficiency and reducing production costs. By leveraging computer simulations, researchers can create more efficient and cost-effective agricultural machinery, save time and eliminate the expenses associated with relying solely on physical prototyping. Finite element analysis has greatly facilitated the development of more sophisticated agricultural equipment. The ability to simulate and analyze the behavior of complex systems, such as the interaction between crop materials and threshing mechanisms, has led to the design of more efficient and effective agricultural machinery (Li et al., 2020).

One area where the finite element method has proven particularly useful is the modelling of heat transfer and phase transformations during the production of agricultural components. For example, metal parts manufacturing for agricultural machinery, the finite element method can simulate complex thermal and material changes that occur during rapid manufacturing processes, such as additive manufacturing. This enables for the optimization of process parameters, improving the quality and performance of the final product (Crespo, 2011).

Table 1 shows examples of studies on agricultural machinery, structures and products using FEM. Machine and system-work group studies are classified, and the software used for simulations is listed as well.

Table 1. FEM applications in Agricultural Machinery

Çizelge 1. *Tarım makinalarında SEM uygulamaları*

Machine / System - Work Group	Machine-System-Product	Intended use of FEM	FEM software used	Source
Tillage Machines	Chisel	To perform stress analysis of the diagram under normal operating conditions	ANSYS Workbench	Çelik et al., 2007
	Cultivator (narrow share)	Determination of equivalent stress values and deformation values under different loading conditions	SolidWorks Simulation	Altuntaş et al., 2018
	Plow	Simulating the draft force in tillage with a plow	EDEM	Üçgül et al., 2018
	Cultivator	Simulating the mixing rates of soil and organic matter of the cultivator	EDEM	Üçgül, 2019
	Cultivator	Calculation and simulation of the stress and strength values that occur during tillage in the cultivator duck sweep share	ANSYS	Chiorescu et al., 2016
	Cultivator	Simulation of the effect of cultivator shares with different share structures on traction forces at different feed rates	ANSYS	Boydaş, 2023
	Cultivator (Duck Sweep Share)	Simulation of stress and deformation values of different cultivator duck sweep shares under different loads	SolidWorks	Aslan et al. 2018
	Subsoiler	Simulation of soil stress and deformation values during tillage at different feed rates of the duck sweep share cultivator	Altair EDEM	Pásthy et al., 2024a
	Rotary Tiller	Simulation of stress and deformation values in motion transmission gears	Cosmosworks	Topakcı et al., 2008
	Subsoiler	Simulation of the dredge force and deformation values of the bottom boiler under different operating conditions during tillage	COSMOS/M	Mouazen & Neményi, 1999
	Mouldboard Plow	Simulation of the effects of the plow's cutting depth, working speed, cutting angle, and lifting angle on machining forces	ABAQUS	Ibrahimi et al., 2015
	Mouldboard Plow	Simulation of stress and deformation during tillage in the plow share	CATIA R15	Chiorescu et al., 2017
	Cultivator	Simulating the combination of DEM and FEM in tillage by passive vibration of shares made of different materials	Altair EDEM	Pásthy et al., 2024b
	Plow	Simulating tillage with a cylindrical plow	ABAQUS	Azimi-Nejadian et al., 2019
	Chisel	Simulation of stress and deformation because of forces acting during deep tillage	ANSYS	Kešner et al., 2021
	Chisel	Determination of safe working conditions of the 7-legged chisel in different soil conditions	ANSYS	Yang, 2024a
	Chisel	Determination of the amount of stress and deformation in the scratch feet under different tillage conditions	ANSYS	Yang, 2024b
	Chisel	Determination of the amount of stress and deformation in the scratch foot and shares	ANSYS	Sharma, 2024

Table 1. Continued

Çizelge 1. *Devamı*

Machine / System - Work Group	**Machine-System-Product**	**Intended use of FEM**	**FEM software used**	**Source**
Tractor	Seat/Operator's Seat	Ergonomic improvement of tractor operator seats	ABAQUS	Daeijavad & Maleki, 2016
	Gearbox	Simulation of stress and deformation during loading in the tractor gearbox	ANSYS Workbench	Dong et al., 2022
	Bottom Connecting Rod	Simulating the stress on the lower connecting arm during tillage	ANSYS	Simonović et al., 2024
Agricultural Trolley	Tow Hitch	Simulating stresses and deformation of drawbars	ANSYS	Zeytinoğlu, 2006
	Axle	Determination of the locations of the use of the software in agricultural machinery through the example (axles of agricultural carts in different sections)	ANSYS	Terzi et al., 2021
	Chassis, axle, fittings	Simulation of stress, deformation, and coefficient of safety under different loads in the Agricultural Trolley	-	Sayıncı et al., 2021
	Chassis	Simulations of stress and deformation values of land vehicle chassis under different loading conditions	SolidWorks	Özden & Gökçe, 2023
Harvesting Machine	Drum Mower	Comparison of the calculated values of the stresses to which the motion transmission shafts are subjected under different operating conditions with the simulation values	ANSYS Workbench	Çelik & Akıncı, 2015; Çelik, 2013
	Fruit Harvesting platform	Simulations of the stress, deformation, and service life of the scissor arms of the designed model	ANSYS 15.0	Eminoğlu et al., 2016
	Overhead Work Platform	Calculation of stress values under static loading conditions and cross-sectional optimizations and selection of the most suitable material	SolidWorks	Ürgün et al., 2020
Spraying Machine	Chassis static strength	Calculation of the stresses of the carrier chassis under force and the total deformation value	ANSYS 2020 R2	Çakmak, 2023
Fertilizer Dispenser	Scraper Shovel	Calculation of stress and deformation values in manure scraper shovel	ANSYS Workbench	Boyar et al., 2020
	Earth Auger	Simulating soil interaction with an earth auger	EDEM	Zhang et al., 2024
	Deep Manure Dispenser	Simulation of stress and deformation values during tillage	Autodesk Inventor	Patuk & Borowski, 2020
Sowing-Planting Machine	Vegetable planting machine	Simulating the loads that occur during sowing and comparing them with field trials	ANSYS Workbench	Wang et al., 2021
Post-Harvest Products	Fruit	Simulating the elastic-plastic deformation of pecan fruit seed shell	ANSYS Workbench	Çelik, 2016
	Fruit	Simulating the equivalent tensile and reaction forces of the impact effect in pear fruit	ANSYS Workbench	Çelik & Akıncı, 2016
	Sugar cane	Simulating the shear force generated during sugarcane harvesting	ANSYS	Yang et al., 2021
	Grapefruit	Simulating susceptibility to mechanical damage under an external clamping force	ANSYS	Ashtiani et al., 2019
	Strawberry	Simulating damage caused by impact during transportation after packaging	ABAQUS	An et al., 2023

Table 1. Continued

***Çizelge 1.** Devamı*

Machine / System - Work Group	Machine-System-Product	Intended use of FEM	FEM software used	Source
Post-Harvest Products	Apple	Determination of deformation and rheological properties of apple fruit under static and dynamic loading under different temperature conditions	ABAQUS	Chavoshi et al., 2023
	Corn/Maize	Simulating damage caused by corn grains colliding with different surfaces	SolidWorks	Guan et al., 2023
	Apple	Simulation of rotting in apples and comparison of volume measurement method	ANSYS	Xu et al., 2024
Agricultural Structures	Coop	Determination of condensation formed on the outer walls of the chicken coop	-	Küçüktopçu & Cemek, 2021
	Silo	Accurate seismic analysis of silos	ANSYS - EDEM	Çelik & Köse, 2020
	Greenhouse	Simulating temperature equivalent curves in different conditions in the designs of greenhouse floor heating system	Borland Pascal 7.0	Dayıoğlu, 1999
	Silo	Simulating stresses during loading and unloading	ANSYS	Gallego et al., 2015
	Silo	Stress analysis of the flow resulting from different shapes of outlets in storage areas	ABAQUS	Guo et al., 2021
Soil Interaction	-	Simulating the interaction of the bottom boiler with tillage conditions	PLAXIS	Poodt et al., 2003
	-	Simulation of the cutting profile with a tillage element	ANSYS	Tagar et al., 2015
	-	Comparison of DEM and FEM in simulating soil compaction	ABAQUS	Bahrami et al., 2022
	-	Simulating soil compaction	ABAQUS	Cueto et al, 2013
	-	Simulating soil compaction values because of tire-soil interaction under different conditions	ABAQUS	Farhadi et al. 2019
Irrigation Machines	Irrigation Pipe	Stress analysis was performed at a certain working pressure, then determining whether the stresses on the pipe wall were safe or not according to this pressure	-	Zeytinoğlu, 2005
UAV	UAV Wheel	1 and 2. Weight reduction and design improvement of support wheels for UAVs in the category	Autodesk Inventor	Beyaz, 2023
	UAV fuselage	Simulating the stress and deformation values of the load-bearing roof under different loading conditions for the four-propeller UAV	ABAQUS	Martinetti et al., 2018
	UAV body and rotors	Simulating the effects of collisions on rotor shafts of small diameters	Ls-DYNA	Zhang et al., 2021
	UAV fuselage	Simulation of static and dynamic stresses of four-propeller UAVs under different operating conditions	ANSYS	Singh et al., 2020

CONCLUSION, DISCUSSION and RECOMMENDATIONS

As a result of the studies conducted in the field of engineering, the finite element method stands out as one of the important techniques used in solutions of problems where analytical and mathematical analysis are challenging. FEM occupies an essential place in the design and optimization of agricultural machinery. With this method, designers can design machines with durability and high efficiency appropriate for loading conditions. Çelik & Akıncı (2015) simulated the stress values in the shafts used for motion transmission in the drum mower and compared them with analytical calculations. They reported that the results of the simulation and analytical calculations had an acceptable error margins.

By evaluating machine components and systems through simulations, designers can optimize their performance, maintain their durability at the necessary levels and reduce production costs. Ultimately deliver agricultural equipment that is more productive, energy-efficient and tailored to the specific needs of the agricultural industry. Ibrahmi et al. (2015) reported that FEM can be used in determining the design and operating conditions of eared plows in their study. They also reported that it can be used to determine the shrinkage force, energy requirements and soil tilting effect. Özden & Gökçe (2023) reported that the equivalent stresses calculated under different loading conditions they simulated in their study were within safe limits for the material. Zhu et al. (2023) simulated soil milling knives in post-harvest tillage conditions in a paddy field. When they compared the results of the simulation, they made by combining FEM and DEM with field trials, they reported that the error rates were below 5%.

Therefore, FEM has become an important tool in the design and optimization of agricultural machinery. Using FEM in agriculture enables rapid prototyping, component optimization, structural integrity enhancement. The integration of FEM with emerging technologies can further improve the performance of agricultural machinery. With the development of computer technology and the increase in processing capacities, faster and more precise analyses will be possible in the future. In addition, by combining artificial intelligence and machine learning techniques, FEM analytics can be made smarter and more predictable. It is important to compare the results obtained from field trials with simulations and to improve the sensitivity and accuracy of the analysis of software. Future research is important because it will contribute to the advancement of current practices.

Data Availability

Data will be provided upon reasonable request.

Author Contributions

Conception and design of the study YSS, BÇ; sample collection: YSS; analysis and interpretation of data: YSS, BÇ; statistical analysis: YSS, BÇ; visualization: BÇ; writing manuscript: YSS, BÇ.

Conflict of Interest

There is no conflict of interest between the authors in this study.

Ethical Statement

We declare that there is no need for an ethics committee for this research.

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