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The Finite Element Method Applied to Agricultural Engineering: A Review

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Abstract

The use of numerical simulations has been widespread in many engineering fields and related areas. One of the main numerical methods used in modeling and simulations is the finite element method (FEM). Despite its wide dissemination, especially in mechanical and civil engineering, FEM has high potential to be applied in other areas, such as in agricultural engineering. This paper aims to present a review of the FEM applications in three agricultural engineering areas. This research is focused on agricultural mechanization, agricultural product processing and soil mechanics, since these are agricultural engineering areas with highest number of publications using FEM. As result, it is expected greater FEM dissemination in other agricultural engineering areas. In addition, modeling and simulation techniques can be widely used in order to represent the increasing behavior of agricultural machinery and products from real physical systems.

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Introduction

The increasing processing capacity in the development of computational resources has made the use of numerical simulations disseminate over the years in several engineering areas.[1] A model can be defined as a representation (approximation) of a real physical system through equations, usually differential ones, and can be described by a finite or infinite number of degrees of freedom, which characterize discrete or continuous problems, respectively. Numerical methods are used as alternatives to obtain approximate solutions to problems when an analytical solution cannot be developed.[2,3,4]

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Based on numerical procedures allied to computational resources, the solution of typical engineering problems can be obtained, except when the model discretization is very large, since the computer capability in these cases may be limited. Numerical methods involving geometric domain discretization is being proposed to solve problems that not show exact analytical solution from mathematical methods. The finite element method (FEM) is a numerical procedure for solving physical problems governed by differential equations. The origin of FEM cannot be accurately predicted since its basic principles date back more than 150 years; however, the first publications mentioning the FEM are from the mid-50s and a significant advance in its development occurred between the 1960s and 1970s.[5,6,7,8] This method is based on discretizing the domain region of the problem, formulating approximate equations, developing and solving these equation systems, and calculating the variables of interest.[2,4]

The FEM results in determining approximate values of desired parameters at specific points such as force, velocity, displacement and stress, called nodes, from linear or non-linear equation systems. A continuous approach function is assumed to represent the solution at each node. The approximate complete solution of the problem is defined by local interpolations in each element (set of nodes), which has continuity guaranteed by establishing previously a connectivity among the nodes. When the size of elements tends to zero and the number of nodes tends to infinity, then the exact solution is obtained.[3,4,9]

The equation of motion for systems with multiple degrees of freedom subjected to external requests is represented in Equation 1. The system characteristics are the input parameters of analysis, and are represented by mass, stiffness and damping matrices. The vector of external requests represents parameters that cause deformations. It is important to understand the role of these parameters and boundary conditions of the system in the FEM modeling.[8]

$$[M]\{\ddot{x}\} + [C]\{\dot{x}\} + [K]\{x\} = \{F\} \quad (1)$$

Where $\{F\}$ is the vector of external loads; $\{\ddot{x}\}$ is the acceleration vector; $[M]$ is the structural mass matrix; $\{\dot{x}\}$ is the velocity vector; $[C]$ is the damping matrix; $\{x\}$ is the displacement vector; and $[K]$ is the stiffness matrix.

Despite the use in engineering areas, such as in mechanical and civil engineering, the FEM is still not widely used in agricultural engineering applications. Comparatively, even though this sector is responsible for the world production of food, fiber and energy, the agricultural sector has applied little the computational modeling and simulation tools for the development of technological innovations. It is desirable that this production gives sustainably without affecting biomes, seeking natural preservation of resources. Increasing productivity is one of the alternatives to increase global supply, especially for the food sector. However, to improve the performance of production systems and increase productivity, it is necessary to develop systematically technological solutions transferred and absorbed by the several sectors from the agribusiness supply chain.[10]

According to the projections of the United Nations (UN) Food and Agriculture Organization (FAO),[11] an increase in the agricultural productivity around 60% is expected by 2050 to meet the global needs. In this context, agricultural sector should develop new technologies at all production stages in order to increase the productivity of already cultivated areas, however, without increasing environmental impacts.[10] FEM applications in agricultural engineering is highly relevant to the agricultural sector since it allows understanding and maximizing the production processes, which is one of the main concerns of the sector in order to meet world food demand without necessarily using new areas.

The present review shows some FEM applications in the main areas where the method is used as a solution in agricultural engineering. Articles were selected from a survey to emphasize the real use in agricultural engineering, besides presenting advantages and disadvantages, and some innovations and evolutions of the FEM.

FEM Applications in Agricultural Mechanization

One of the agricultural engineering areas that can be benefited from the increasing use of FEM is the agricultural mechanization through two strands. The first one is related to the modeling and simulation of agricultural machinery and implements in order to obtain reliable data on the structural and mechanical behavior of machinery, detect possible damages, maximize the production process and optimize designs of parts, machinery and equipment. The second is the modeling and simulation of the interaction between machinery and plants in order to predict the biological behavior of materials involved in the cultivation, harvesting, post-harvesting, drying, storage and other processes (Table 1).

The numerical simulations are able to allow studying the behavior of products without needing to create prototypes, thus assisting both in the manufacturing process and in monitoring the feasibility of use, detecting possible usage or material failures.

Oliveira *et al.*[13] modeled and simulated a mechanical joint composed of a tractor and a coffee harvester to measure the highest stress points in order to improve the equipment operation. The model that represents the coupling in the trawl is composed of connecting rod and lever and discretized by second-order tetrahedral elements. The lever model used 9,085 elements and 15,757 nodes, and the connecting rod used 8,472 elements and 14,715 nodes.

The input parameters were taken from the literature and obtained as responses the maximum values of the von Mises stress at the critical point of each piece, which was approximately 7.84e6 $N.m^{-2}$ for the connecting rod and $3.92.10^6$ $N.m^{-2}$ for the lever. The use of von Mises stress allows the designer or operator to infer about the integrity of the mechanism through the theory of linear elasticity, which can reduce the amount of material used in its construction or aid in decision making regarding the maintenance of the mechanism. Results found from simulations showed an error of only 4.3% in relation to the experimental ones and the model allowed localizing likely failure regions.

The performance of a tractor's wheel at different inflation pressures was simulated by Inaba and

Table 1: Use of FEM in agricultural mechanization

Author	Year	Studied variable
Savary *et al.*[12]	2010	Dynamic behavior in an orange tree model.
Oliveira *et al.*[13]	2014	Connection between drawbar and coupling system of a coffee harvester.
Silva *et al.*[14]	2014	Stress concentration in a coffee harvester model.
Tinoco *et al.*[15]	2014	Dynamic behavior in a model of the coffee fruit-peduncle system.
Santos *et al.*[16]	2015	
Inaba and Hiroma[17]	2015	The performance of a tractor's wheel at different inflation pressures.
Coelho *et al.*[18]	2016	Dynamic behavior in a model of the coffee fruit-peduncle-branch system.
Fu *et al.*[19]	2016	Dynamic behavior in an sea buckthorn tree model.
Carvalho *et al.*[20]	2016	Stress concentration in a coffee model.
Hoshyarmanesh *et al.*[21]	2017	Dynamic behavior in an olive tree model.
Li *et al.*[22]	2017	Penetration resistance of a cutting tool model in soil with maize roots.
Ebrahimi *et al.*[23]	2018	Dynamic behavior in a model of a scarifier rod.
Silva *et al.*[24]	2018	Static and modal frequency simulations in a coffee harvester`s chassis
Souza *et al.*[25]	2018	Evaluation of the interaction between a harvester rod and a coffee branch based on finite element analysis

Hiroma.[17] In this study, the authors used an anisotropic elastic wheel model that included vertical and horizontal rigidities, in order to simplify the three-dimensional models normally used for two-dimensional analysis by using tire, and soil models and a model from the friction between the tire and the soil. In this case, the Coulomb friction law was used for the friction model. The model was discretized by rectangular elements and the mesh was refined in the points of contact between the ground and the tire. In the simulations, the wheel was rotated adapting displacement increments between the contact nodes. In order to validate the model, a structure representing a tractor wheel was used to obtain the results of traction force and torque in the axis that were later compared to the values of distributed normal stress obtained from the simulations. Results showed agreement around 89%, demonstrating that the model was able to simulate the tire behavior. Silva *et al.*[14] and Silva *et al.*[24] modeled the coffee harvester structure and performed static and dynamic analysis to verify concentration points of stresses and displacements for two situations: the machine working with aligned rear wheels and the machine working with misaligned rear wheels. The mesh used for the model discretization was formed by triangular prism elements with sizes between 1.2 mm and 47.0 mm, generating 35,121 nodes. The simulation input data was taken from the SolidWorks software database. The model with misaligned wheels showed displacement values around 11.9% lower than the model with the aligned ones. The maximum von Mises stresses for both situations were close, showing a difference of only 1.9%. This paper had no intention to show any dynamic effects of a coffee harvester machine and this can be considered a limitation of the presented work.

Li *et al.*[22] modeled soil resistance with maize roots to penetration of a cutting tool. The soil was modeled as elastic-plastic material and the maize roots were considered as lines with different diameters. Two cutting blades represented the tool, one with the straight edge (A) and the other with serrated edge (B). Two different speeds were considered in the simulations, which were then compared with experimental data. The elements used in the model discretization were taken from the Abaqus software database. In the model of blade A, the C3D8R element (eight-node hexahedron) was used, forming a mesh of 182 nodes and 79 elements; in the models of blade B and soil with maize roots, the C3D4 element (four-node tetrahedron) was used, in which the meshes consisted of 1,331 nodes and 4,285 elements, and 115,707 nodes and 66,193,810 elements, respectively. The agreement of the simulation results with the experimental results was above 87%. The authors considered the FEM as a convenient and reliable prediction tool in the analysis and development of the working capacity of the crop tool. The use of the Abaqus software and other software gives us an idea of the diversity of use of the FEM.

Fatigue study can be performed considering that evaluated structure works under periodic excitation as in the case of subsoils and scarifiers. Ebrahimi *et al.*[23] simulated a scarifier shank model from a modal analysis in order to predict the fatigue life of implement shank using the Wirsching-Light and Dirlik methods. To this end, the developed model was based on the geometric properties of samples. The subspace stochastic technique was chosen to be used, since it does not require known input variables. The model was discretized by tetrahedral elements and experimental vibration data were measured at four points of the shank with the equipment in use. The highest error found between experimental and simulated results was 5.6%, thus validating the use of the model.

The approach in which it is possible to obtain the behavior of biological materials using the FEM has been used in the agricultural mechanization area, mainly in cultures that use the principle of mechanical vibrations to promote the detachment of its fruits during the harvesting process. These types of studies date back to the mid-1970s and generally consider structures as elastic, homogeneous, and isotropic.[26]

Dynamic behavior of a coffee tree was simulated by Tinoco *et al.*[15], Santos *et al.*[16], Coelho *et al.*[18] and Souza *et al.*[25]. Authors used models from part of a plant, such as fruits, peduncles and branches, based on approximations made in specific software of computer aided design (CAD) in order to perform dynamic simulations. Coelho *et al.*[18] used a stochastic approach to determine the natural frequencies of the fruit-peduncle-branch system, using stochastic fields of the model input data (elasticity modulus and specific mass). However, Santos *et al.*[16] and Tinoco *et al.*[15] worked in a deterministic way to determine the natural frequencies of the fruit-peduncle system, using input data with from the average of the samples collected to determine the input data.

Tinoco *et al.*[15] worked on a model composed of peduncle, pedicel and fruit. The fruit and peduncle were discretized by meshes composed of tetrahedral elements, while the peduncle was discretized by a mesh composed of hexahedral elements. This difference between elements used occurs to obtain an improvement in the discretization of the model aiming at a better representation of the boundary conditions and a lower computational cost. The study of Santos *et al.*[16] used a standard unstructured mesh with 10,216 tetrahedral elements and 1,988 nodes. In the study of Coelho *et al.*[18], the mesh composition was made by ten-node tetrahedral elements. In all the three cases, it was noted that the natural frequency value decreased with the evolution of the maturation stage of fruits. This behavior is explained by the loss of rigidity of the product with the evolution of the maturation stage. The fundamental frequency values resulting from numerical simulations were close in the three studies[15,16,18,] between 17 Hz and 20 Hz for mature fruits and between 18 Hz and 23 Hz for immature fruits.

System behavior analysis can also be performed by using static analysis, such as in Savary *et al.*[12]. Authors developed three models of orange tree and performed the simulations in a deterministic way in order to analyze the maximum and minimum deformations occurring when the plant is stressed at pre-established frequencies of 3 Hz and 3.83 Hz. Models were developed in SolidWorks commercial software and simulated ANSYS. Input variables were pre-determined in laboratory tests. Discretized meshes used three-dimensional tetrahedral elements. The model was able to represent 50% to 60% of the real physical system. However, authors emphasize that through a more complete model using wood anisotropic characteristics, simulation results can be improved.

Fu *et al.*[19] simulated the dynamic behavior of sea buckthorn in order to establish a database for the development of crop harvesting machines. In their study, authors used a model developed in Pro/ENGINEER software and simulations in ANSYS software. The experimental setup was performed from a randomly selected five years old tree. In the system simulations, modal analyzes were performed, extracting main natural frequencies and vibration modes. Harmonic response was also analyzed when the steady state of the system was subjected to an external load. For the branches model from the tree, it was assumed a circular cross section was and the diameters were obtained from direct measurements from experimental samples. However, some regions of the branches were considered thin and they were not shaped / measured.

Experimental sample were submitted to laboratory tests in order to determine main mechanical properties required as inputs for the simulations. The model discretization was performed by eight-nodes tetrahedral elements which resulted in a model with 424,552 elements and 107,843 nodes. The model was considered elastic, isotropic and identical and the Block Lanczos method was used in this study.
In this case, first 20 natural frequencies were extracted and values between 6.6 Hz and 31.8 Hz were found. Each extracted mode represented a vibration in different parts of the tree, however authors noticed a tendency of lower frequencies act on the branches and higher frequencies act on the trunk. Harmonic analysis demonstrated that the vibration in the trunk is inefficient, while the lateral vibration to the branches proved to be most appropriate. In addition, the point of load application between 58 N and 78 N acts frequencies between 20 Hz and 30 Hz, which proved that fruits could be detached. This study demonstrates MEF efficiency in predicting behaviors and uses them as a basis for machine design. Authors suggested that new simulations relating the applied load to the geometry of the branches and application points can improve the understanding of the dynamic behavior of sea buckthorn and improve the harvesting efficiency.

Carvalho *et al.*[20] statically modeled and simulated a coffee plant in order to predict displacements and stress concentration regions. The model used in the experiments was developed using reverse engineering from the trunk scanning from a coffee plant. In the model discretization, the authors proceeded with mesh refinement tests, reaching

Table 2: FEM usage in agricultural product processing

Author	Year	Studied variable
Vagenas and Marinos-Kouris[27]	1991	Development of fruit and vegetable models.
Dintwa *et al.*[28]	2008	Dynamic behavior in apple models.
Ambaw *et al.*[29]	2011	Kinetics of gas diffusion/adsorption in apple models.
Celik *et al.*[30]	2011	Stress concentration in apple models.
Nilnont *et al.*[31]	2012	Drying in a two-dimensional model of parchment coffee grain.
Li *et al.*[32]	2013	Stress concentration in tomato models.
Abbaszadeh *et al.*[33]	2014	Modal analysis in watermelon models for maturation prediction.
Pieczywek and Zdunek[34]	2014	Determination of stress-strain curves in a 2D model of onions.
Ahmadi *et al.*[35]	2016	Dynamic behavior in apple models.
Yousefi *et al.*[36]	2016	
Celik[37]	2017	Dynamic behavior in pear models.
Salarikia *et al.*[38]	2017	

a mesh with ten-node tetrahedral elements of approximately 2 mm. The displacements observed in the simulations represented up to 80% of the shortest branches and up to 46% of the longest ones, being this difference explained by the stiffness of the material. The developed coffee model represents an advance for future static or dynamic simulations, both of coffee itself and simulations involving the plant interaction with machinery and implements used in the coffee harvest.

Hoshyarmanesh *et al.*[21] obtained olive tree simulations for the prediction study of dynamic behavior from the system. Important parameters were considered for the system simulation, such as wood anisotropy, dynamic behavior of temperature and water content, and a more representative three-dimensional model. Authors described that this kind of analysis was able to optimize the efficiency and productivity of mechanized harvest system. The model was developed based on geometric properties of tree samples and was discretized by standard three-dimensional tetrahedral solid elements. As boundary condition, an orbital load was applied in terms of pressure. Simulation results showed less than 5% difference among the experimental results, highlighting the relevance of the dynamic analysis to improve the fitting parameters of the harvesting process.

These studies show the versatility of FEM within the area of agricultural mechanization by using different software, models and elements to perform the simulations.

FEM Applications in Agricultural Product Processing

The knowledge of the physical properties of biological (agricultural) products is also of great industrial interest in applications in order to perform processing steps such as transportation, drying, separation and classification (Table 2).

With the aid of FEM, the determination of such properties has been made accurately since the mid-1970s, when Rumsey and Fridley39 used the method for viscoelastic contact analysis in horticultural crops.

Vagenas and Marinos-Kouris27 proposed general models to be used in drying simulations of fruits and vegetables. The authors presented a theoretical basis in FEM used in the simulation of models, pointing out the difficulties on its use, since agricultural products do not show a standard geometry. The proposed methodology was applied in currants, apricots, potatoes and carrots, being observed that the mesh refinement significantly improved the model response in relation to the real physical systems.

In the models used in currants and apricots, the authors used an ellipsoid shape with symmetric axes, which is not desirable in simulations because the boundary conditions of models may be asymmetric. In the ellipse center were used hexahedral elements while a combination between hexahedral elements and triangular prisms was used in the edges. Regarding the currant, 21 elements were used to represent the quarter section of the model in the xy direction, while this number was 30 elements for the apricot and a series of six elements were used to represent the length of both fruits in the z direction. Potatoes and carrots models were discretized, represented by prismatic elements with arbitrary shape. In xy cross section plane, 40 elements were used, considering three elements along the z-axis in order to represent the model thickness. In this way, the used mesh showed 126 elements in a total of 196 nodes for currants, 180 elements and 168 nodes for apricots, and also 204 elements and 276 nodes for potatoes and carrots.

The authors obtained satisfactory results with the models developed. In this study, the difficulty of representing agricultural products in numerical simulations is evident. However, FEM was considered adequate to predict the drying behavior for products of different shapes and sizes. The ability to represent is an advantage of the FEM.

The grain behavior during drying is a way of predicting drying kinetics, volumetric shrinkage and mechanical damages that can cause waste and fall in the market price of agricultural products. In this sense, the FEM is an important tool to predict grain behavior during drying, similarly as in the study of Nilnont *et al.*[31], which described the drying kinetics in a two-dimensional model of a parchment coffee grain through FEM. The model developed by the authors was validated by comparing the simulated with the experimental results obtained. A mesh composed of 210 symmetrical triangular elements with two-dimensional central axis was used to discretize the coffee grain model. The results obtained in the simulations showed from 85% to 92% similarity to the observed results for the real physical system.

It is also possible to simulate gas diffusion/adsorption in ovens, such as in the study of Ambaw *et al.*[29] in which the authors simulated a chamber model where the 1-methylcyclopropene (1-MCP) air diffusion was simulated first and then the 1MCP diffusion associated with irreversible adsorption in an apple was simulated. The developed model was a replica of the real physical system, consisting of an apple inside a chamber. A sphere with same volume of the apple fruit was used. Diffusion was also considered as unidirectional and the model was simplified for simulation from a three-dimensional structure to a unidirectional, going through a two-dimensional structure.

Discretization was performed by 40,000 rectangular elements and 7,694 nodes with 64,200 degrees of freedom for the 3D model; by 9,632 triangular elements and 4,865 nodes with 27,200 degrees of freedom for the 2D model; and by 768 straight segments and 769 nodes with 1,922 degrees of freedom for the 1D model.

The one-dimensional model was sufficient to describe the behavior of diffusion and adsorption coefficients in apple. The accuracy of the values was 99.7% and 97.6% for the simulated scenarios. The authors emphasize that the FEM model associated with the non-linear least squares regression can provide a tool with potential to estimate diffusion values and referred gas adsorption behavior using time series data.

The model used must always be able to represent the real physical system, but it is also concerned with the computational cost gain. In this case, authors highlighted the concern with the model, being this one of the advantages in the FEM, since for both three-dimensional and one-dimensional models it was possible to obtain satisfactory results.

Agricultural and food products at different maturation stages have different physical characteristics, which directly influence their dynamic characteristics. Thus, an innovative analysis was performed by Abbaszadeh *et al.*[33] when using the modal analysis of watermelon for prediction of its maturation stage. The model used in this study was developed from the geometric characteristics. 35 samples and discretized three-dimensional rectangular elements of 20 nodes with three degrees of freedom were used. Simulated results showed agreement around 99.4% when compared to experimental data.

The development of numerical methods allows working the non-linearity of models and dynamic behavior efficiently, being possible to predict resistance to impacts and injuries in agricultural and food products, without the need for destructive tests, which aids to optimize the harvesting and post-processing, and the development of more suitable packaging and transportation systems. Through the FEM, scenarios that allow a better understanding of the product behavior when stressed externally can be simulated. Similar studies were already performed with pears[36,37,38,] apples[28,29,35,] tomatoes[32] and onions.[34]

In the pear studies, the authors analyzed the behavior of fruits subjected to impacts of different heights (from 0.25 to 1.0 m) on different surfaces (steel, wood and rubber) and with different fall directions (between 0º and 90°). The elements used for the discretization of models were ten-node tetrahedrons with a maximum size of 3 mm. The choice of this element is justified by its high accuracy and good representativeness of the shape boundary. Celik37 used model discretization by using hexahedral elements. A mesh with 518,894 elements and 108,835 nodes was used for simulations. In Yousefi *et al.*[36] and Salarikia *et al.*[38], meshes were used with 8,866 nodes and 6,123 tetrahedral elements, and 38,917 nodes and 33,198 tetrahedral elements, respectively. In Celik[37], authors modeled the fruit from a surface scanning, which represents an evolution in obtaining the model, since the authors can guarantee a more realistic view of the deformation behavior in relation to the models generated by CAD software. In both studies, physical properties of pears were used as input parameters in the simulations. Salarikia *et al.*[38] did not validated experimental results, whereas other studies showed agreement of up to 99% between experimental and simulated results.

Similar analyses were performed with apples. In Dintwa *et al.*[28] and Ahmadi *et al.*,[35] half apple models were developed, since pendulum experiments that were used for validation in these studies use half apples. However, in the study of Celik *et al.*[30], the model was developed from the scanning of an apple, representing an evolution in obtaining the model. Tetrahedral elements were used for the discretization of the finite element model. In Celik *et al.*[30], the mesh consisted of 37,203 elements and 43,828 nodes, whereas in the study of Dintwa *et al.*28, a refinement was used for each part of the model (666 elements in the shell, 2610 elements in the cortex and 294 elements in the apple core).

One of the important issues in a FEM analysis is selecting the appropriate element size. Mesh density is used to control the model accuracy and a smaller element size produces results more accurately. The selection of the mesh together the best element type should be done by designers from pre-simulation procedures. In this case, model's solution time must be taken into account for each mesh structure. The mesh chosen should be the one that best represents the model with the lowest computational cost. The authors found that although there are limitations on the FEM usage, they agree that the use of numerical simulations associated with digital models are very useful tools in predicting the behavior of biological materials for non-destructive testing and may be economically beneficial to examine damages in agricultural products.

Li *et al.*[32] performed experiments using 3D models to predict stress concentration areas inside tomatoes. In this case, three models were used and the model discretization was performed considering two tetrahedral elements in ANSYS software database. The mesh used for the model discretization had 2 mm elements to represent the exocarp and mesocarp, and 1 mm to represent the locule gel tissue. In the first model, the mesh consisted of 19,402 elements and 29,256 nodes, in the second by 21,824 elements and 41,601 nodes, and in the third by 22,878 elements and 53,239 nodes. In this study, the authors state that the nonlinear multiscale finite element method was able to predict from 65% to 92% of the internal mechanical damage behavior of tomatoes under different loading conditions.

Table 3: FEM usage in soil mechanics

Author	Year	Studied variable
Nielsen et al.40	1986	Literature review for numerical methods that solve the Richards Equation.
Milly41	1988	
Leib and Jarrett42	2003	Prediction of pesticide dissemination in the soil using the LEWASTE model.
Poodt et al.43	2003	Simulation of the compressive strength of the soil subjected to sugarbeet harvester traffic.
Bunsri et al.44	2008	Use of the Galerkin method to solve a model that predicts the sodium chloride diffusion in the soil.
Xia45	2011	Soil compaction behavior and tire mobility.
Hemmat et al.46	2012	Resistance to soil compaction.
Cueto et al.47	2016	Modeling of soil pressure distribution under agricultural tire traffic.
Godinho and Soares Jr.48	2017	Use of the adaptive technique BEM-FEM in the simulation of the elastodynamic behavior of the soil.

Pieczywek and Zdunek[34] used the FEM to determine stress-strain curves of the onion epidermis in order to predict the behavior when subjected to traction using a 2D model. The model was discretized using an average of 34,879 first-order triangles that impart plasticity, stiffening, large stresses and large deformation capacities to the model. The thickness of the tissue sample was used as input parameter in the simulation. The model was able to simulate large stresses, with approximations of up to 74% and non-linear behaviors.

Considering these studies, it is possible to have an idea of how the modeling can influence directly in obtaining FEM results and the difficulty that exists in its representation when agricultural products were considered. The convergence of results is influenced directly by the chosen element, being that the more refined meshes (discrete geometric model in nodes and elements) represent the real systems, despite having a higher computational cost.

FEM applications in soil mechanics

The objective of soil modeling by the FEM is to predict scenarios where unknown variables such as the physical interactions occurring in wet and dry soils and the dispersion of solutes in the soil are involved, as well as the diffusion of pollutants and wastes. The knowledge of these variables is important to perform numerical simulations, since they directly influence seed germination and propagation, besides your contamination (Table 3).

A lot of methodologies based on FEM have been developed since the 1980s in order to simulate the movement of solutes in saturated and unsaturated soils, including FEMWATER[49], SUTRA[50], SEFTRAN[51] and HYDRUS in the versions 1D[52] and 2D[53].

In the 1980s, Nielsen *et al.*[40] and Milly[41] performed a review of the deterministic and stochastic mathematical methods that solve the Richards Equation, used to describe the basic processes of water flow and chemical transport in the unsaturated zone of soils. Nielsen *et al.*[40] pointed out that the use of the FEM for this type of approach demonstrates advantages in relation to the other techniques already used due to the ability to describe more precisely the thresholds of the irregular system in multidimensional simulations, besides including more easily the average non-homogeneous properties. The method leads to more stable and accurate solutions with computational resources more efficient. Milly[41] emphasized that the Richards equation is more accepted for water flow analysis and the stochastic technique can be applied to this equation for solving the natural soil heterogeneity. Milly[41] also showed that the control of a computational problem must be performed carefully on the mesh construction in the FEM, especially the care in the position of nodes in space and time.

Soil pesticide movement was also simulated by Leib and Jarrett[42] using a model simulated by the FEM in order to compare the predicted and measured concentration of pesticide in the soil during its effectiveness period. The model was evaluated and validated based on data from a field study in which the pesticide was applied to control cucumber beetles. The governing differential equations were also solved by the Galerkin method[2], considering the nonlinearities arising from the heat exchanges recurrent to the experiment. The model converged to the data observed experimentally, showing errors from 3% to 17%, being efficient to represent the pesticide movement in the soil.

Bunsri *et al.*[44] simulated the movement of sodium chloride as a tracer in the soil at 5 and 20 cm depths. For the model numerical solution, they used the Galerkin method[2]. The results obtained in the simulation represented from 80% to 93% the results observed experimentally, demonstrating capability to simulate all the marker transport conditions and to estimate effectively the dispersion coefficients.

Soil compaction caused by traffic from agricultural machinery can also be simulated by FEM. Poodt *et al.*[43] simulated the soil behavior when subjected to the sugar beet harvester tires and wheel loads. The soil mechanical properties were known and used as input parameters of simulations. As output parameters, the authors calculated the preconsolidation stress, the compression index and soil dilatancy, all as a function of depth. Sizes, pressures and loads were simulated on the most common tires used for harvesting. Several soil cohesion levels were used because this information was not available. Detection of Coulomb plasticity areas was also included. In the simulation results, no compaction was found at great depths. The authors highlighted the lack of practical methods for validation of these models and the need to perform a sensitivity analysis on the input parameters.

Similar analysis was performed by Cueto *et al.*[47], in which the authors simulated the soil compaction occurred by the passage of a tire at different loads, inflation pressures and in different soil moisture. The generated model represented a soil track with a tire and was simulated in the Abaqus software. The model discretization was made by the element C3D8R (eight-node hexahedron), available in the software database. The element size was between 1 mm and 2.5 mm, and the mesh was more refined in the contact between the ground and the tire, and less refined inasmuch as it moved away from the contact. This refinement type improved the computational efficiency. The simulation results allowed the authors suggesting the shape, magnitude, distribution and depth transmission of the stresses underwent by the dry and moist soils when subjected to the traffic of agricultural tires.

Xia[45] used the FEM to predict transient spatial density and tire deformation. The formulation was used to capture the change in configuration at the ground horizon in contact with the tire, which combined with the elastoplastic model can be used to calculate the transient spatial density due to tire compaction in the ground. The author presented an innovative characteristic of modeling the spatial density change, which is desirable for the study of geotechnics, both in agriculture and civil engineering. The developed numerical model proved to be a robust tool, which can be used to predict soil compaction behavior and tire mobility.

Hemmat *et al.*[46] studied soil compaction with a different approach than that presented by Xia[45], in which the authors used the FEM in simulations considering the viscoelasticity to represent the soil compression curves and to understand their behavior when subjected to static loads. The model used by the authors allowed simulating the compaction effort and predicting the soil physical properties, occurring similarity of 69% among the simulation and experimental results.

Although the results are close to the real ones, studies need to be done to improve these results. Development of models closer to real ones and knowledge of input data are of fundamental importance to this type of simulation.

Godinho and Soares Jr.[48] researched coupling technique from methodologies that lately was used in several studies. Godinho and Soares Jr.[48] used

FEM and BEM (boundary element method) jointly to simulate the elastodynamic interaction of the soil. Coupling of methods allowed independent discretization, which makes the equation systems generally better conditioned, providing improved solutions.

In this technique, one of the domains remains unchanged, being its matrices computed only once while the other undergoes an adaptive refinement of the model discretization inasmuch as the solution is evolved, thus making the solution more efficient. To couple both methods, it is necessary to impose the continuity and equilibrium standard equations on the common interface. The iterative process is based on the successive transfer among the coupled domains. In the present study, there are two types of iterations: displacements prescribed in BEM and stresses prescribed in FEM and vice versa. Adaptive refinement can be described in four stages: the current mesh solution is determined; error is estimated at nodal displacement times; this error is used to select a set of elements to be refined; and finally the selected elements are refined. The authors used the coupling technique to simulate four applications as follows: (i) introduction of a solid structure into an infinite solid medium (soil), (ii) opening a soft soil trench in a more rigid semi-infinity soil, (iii) a concrete wall interacting with the surrounding soil, and (iv) introduction of a three-dimensional solid into a homogeneous medium. In conclusion, the authors emphasize the advantage of using meshes and independent solutions using the best method for each part of the model and without increasing the computational cost.

In the studies presented here, it is clear the advantages of using FEM in agricultural engineering which is linked to the technology knowledge in this research field. In addition, a breakthrough is presented when using the FEM associated with other consolidated methods.

Final considerations and future perspectives

The present paper presented a review on the FEM usage in the main areas of agricultural sciences. The use of FEM has been well accepted in the areas of agricultural mechanization, agricultural product processing and soil mechanics.

Based on this review, it was possible to observe that, regarding the agricultural mechanization, the FEM is mainly used in the field of machine design and prediction of dynamic behavior in several structures and agricultural machinery. For processing of agricultural products, it was verified that the FEM could be used to obtain physical characteristics of products and prediction of the mechanical behavior when subjected to drying. Finally, in soil mechanics, it was observed that FEM could be used to predict the movement of solutes in soils, among other applications.

In order to expand the use of FEM in agricultural engineering, it is expected that further development of agricultural products will be performed and disseminated using this tool in order to obtain models that are closer to real physical systems, thus disseminating the FEM in other agricultural engineering areas. In addition, the Discrete Element Method (DEM) combined with finite element algorithms can also be employed in future agriculture researches.

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