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Deep tillage tool optimization by means of finite element method: Case study for a subsoiler tine

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Abstract

Technologies and computer capacity currently available allow us to employ design software and numerical methods to solve complicated problems in very wide disciplines of engineering. It is also important for researches in agriculture. This study focused on obtaining optimum geometry parameters of a subsoiler tine by using computer aided engineering (CAE) applications. A field experiment was conducted to determine draft force of the subsoiler. The results from the experimental study were used in the finite element analysis (FEA) to simulate stress distributions on the subsoiler tine. The maximum equivalent stress of 432.49 MPa was obtained in the FEA. Visual investigations and FEA results showed that according to the tine's material yield stress point of 355 MPa, plastic deformation was evident. Based on the FEA results, an optimization study was undertaken to obtain optimum geometry parameters without the occurrence of plastic deformation. According to the optimization study results, the optimum parameters of the tine geometry and maximum equivalent stress of 346.61 MPa were obtained. In addition to this, the total mass of the tine was reduced by about 0.367 kg.

Key words: Subsoiler, optimization, finite element method, agricultural machinery design.

Introduction

Plants, which are grown under a controlled environment, need some primary requirements related to soil structure such as enough space for root movement, enough organic material distribution and enough water permeability. Hence, the soil must be prepared for the plants by tillage before seeding and during their growth. However, every year, soil in agricultural land becomes more compacted structure (of about 250 mm of depth) due to the repetition of the tillage process and traffic (wheel compaction) in the field. This soil compaction layer is called the hardpan or plough (plow) pan. This hard layer must be cut into parts because it does not allow plant growth to diffuse and remain healthy. This soil compaction directly affects the plant root in a negative manner, as can be seen in Fig. 1 [1].

Therefore, subsoiling has become an essential tillage operation [2]. One of the most useful methods to avoid soil compaction is deep tillage by using a subsoiler [3]. A subsoiler is a tillage tool that can work up to depths of 450-750 mm under the surface of the land. There are a number of different subsoiler designs in the field but they all serve the same purpose which is deep tillage for eliminating hard layers.

In general, subsoilers are manufactured using steel for the construction. Usually, a subsoiler has a main framework, support parts, tine and a narrow share. Subsoilers work under high level soil reaction forces because of the deep tillage. If a subsoilers' elements are unable to cope with these forces, they become useless due to plastic deformation, abrasion or parts breaking. Hence, the constituent elements of a subsoiler construction must be durable enough during tillage operations. Therefore, it is very important for the designers and agricultural machinery manufacturers to predict deformation and structural stress distributions on the machine elements during tillage operations, which will allow them to manufacture optimised machinery by using predicted knowledge.

Applications are continuously becoming more complex and large scale in the design engineering world. Additionally, available technology, the proliferation of computers and software let design engineers solve complicated problems using computer aided design (CAD) technology and numerical methods in a virtual way without committing to physical manufacture and testing. These applications are typically termed computer aided engineering (CAE). Mechanical design engineering has been improving itself rapidly by using such CAE applications since the 1950's. Although some engineering problems can be solved using analytical methods and/or experimental methods, some problems are too complicated or too large scale to be solved. Hence, engineers refer to numerical methods to obtain approximate solutions for their large-scale and complicated problems. One of these numerical techniques is Finite Element Method (FEM) which has huge usage in the area of mechanical design and in the manufacturing industry. The FEM is a numerical procedure that can be used to obtain

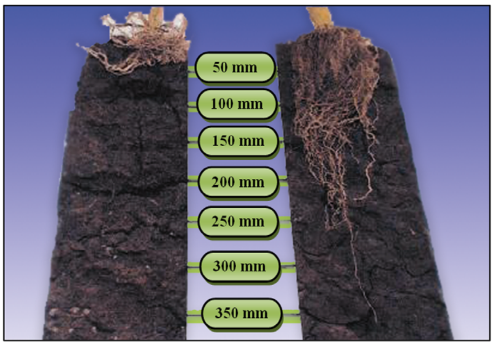


Figure 1. Negative effect of compaction on corn roots in compacted soil (left) and non-compacted soil (right).

solutions to a large class of engineering problems involving stress analysis, heat transfer, electromagnetism, and fluid flow. The method was improved in the 1950's and during the 1960's, investigators began to apply the FEM to other disciplines of engineering [4]. Today, it is possible to see various application samples of FEM in many different disciplines of applied sciences. For instance, they should inevitably be applied in agricultural machinery design processes in today's developing technological era.

In this paper, we present a case study which was carried out to enable the structural optimization of an agricultural tool through using CAE applications. The main purpose of the case study was to provide a sample situation where it was possible to obtain the optimum geometry parameters of agricultural machinery and tools without any plastic deformation under defined boundary conditions. Although much research can be found about subsoilers, its effects or its soil interaction conditions, it can be concluded that there have been limited studies about the structural optimization of the construction and constituent elements using CAE applications. However, a few similar studies related to CAE have been presented in agricultural engineering research. Gameda *et al.* [5] investigated the effect of subsoil compaction on corn production yield under axle load. Mouazen and Nemenyi [6] investigated and analyzed soil-loosening processes in non-homogeneous sandy loam soil with subsoiler using FEM. Zeytinoğlu [7] investigated strength conditions for a support part of a plough by using FEM, and 2D finite element model was created and the equations were solved using Matlab software. The study concluded that there was no failure on the model under the defined boundary conditions. Degirmencioglu *et al.* [8] conducted an optimization study for a framework of plow by using FEM. Stress distributions were investigated by means of FEM simulations and it was suggested that benefits would include material weight reduction on the main frame work. Poodt *et al.* [9] investigated subsoil condition under the heavy wheel load on the sugar beet area. An analysis was made by using FEM for a relevant calcaric fluvial soil profile, the mechanical properties of which were largely known. In the study, it also focused on FEA profits to visualize the soil compaction problems.

Our study focused on obtaining optimum geometry parameters of a subsoiler tine by using computer aided engineering (CAE) applications. A field experiment was conducted to determine draft force of the subsoiler.

Materials and Methods

Field experiment: Computer aided measurement systems were utilized for the field experiment. A two-tractor method and computer-data logger connected dynamometer were used to measure draft force of the subsoiler. The tractor speed was 4 km/h during the tillage operation. The field soil texture was: sand 15%, clay 30% and silt 55%. The study was carried out in BATEM (Batı Akdeniz Agricultural Research Institute) agricultural field test site, Aksu, Antalya, which is located in the West-Mediterranean region of Turkey. Field experiment results were created according to data from data logger, where a maximum draft force of 38,320 N was measured. Subsoiler-tractor-dynamometer connections and field experiment data are presented in Fig. 2 and 3, respectively.

Finite element analysis of the subsoiler tine: All the dimensions were measured on the experimental subsoiler, then a 3-dimensional (3D) solid model and its assembly process were created using Solidworks 3D parametric design software. The 3D solid model of the subsoiler and its significant dimensions are given in Fig. 4.

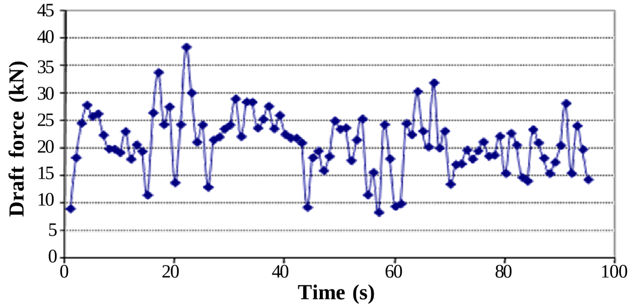
The study focused on the deformation of a single tine of the subsoiler. Therefore, all components of the assembled solid model of the subsoiler were not used in the FEM analysis. The commercial FEM software package, Ansys Workbech, was utilized for the FEM stress analysis process. The FEM analysis was set up in 3D, linear, static and isotropic material model assumptions. When real working conditions were evaluated, the boundary conditions were applied to the model properly. Maximum draft force magnitude for each tine was accounted for according to the experimental study data. The draft force was assumed as 12 ,773 N for each tine that was applied on the surface of the narrow share in the opposite direction of the movement of the tine. Standard steel material properties for St-52 were assigned for the tine material (Table 1).

Ansys Workbench meshing functions were utilized to create a mesh structure of the tine [10], and a 10 Node Quadratic Tetrahedron (10 Node Tetrahedral Structural Solid/Solid 186) element type was

Table 1. Material properties of the tine (St-52).

Properties	Unit	Value
Young's Modulus	[GPa]	205
Tensile Ultimate Strength	[MPa]	520
Yield Strength	[MPa]	355
Poisson Ratio	[-]	0.29
Density	[kgm^{-3}]	7870

Figure 2. Subsoiler-tractor connections, dynamometer and experimental study.



Draft force	Average	Min.	Max.
(kN)	20.94	8.11	38.32

Figure 3. Draft force.

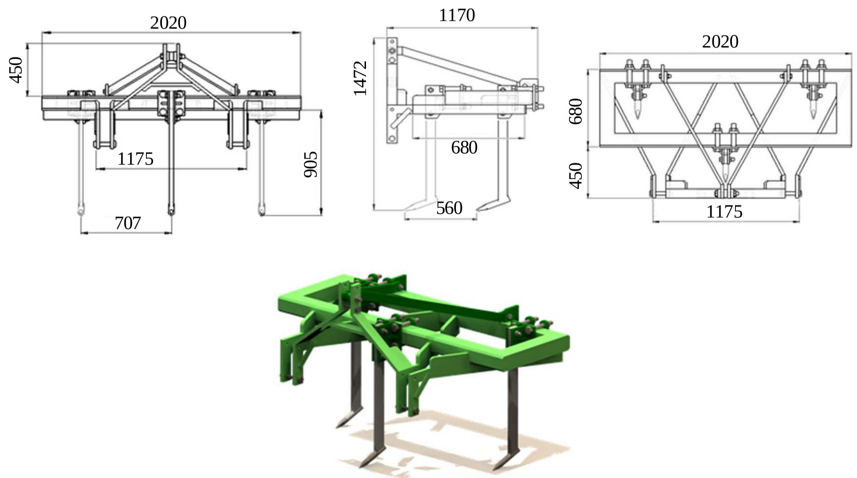


Figure 4. Dimensions and 3D solid model of the subsoiler.

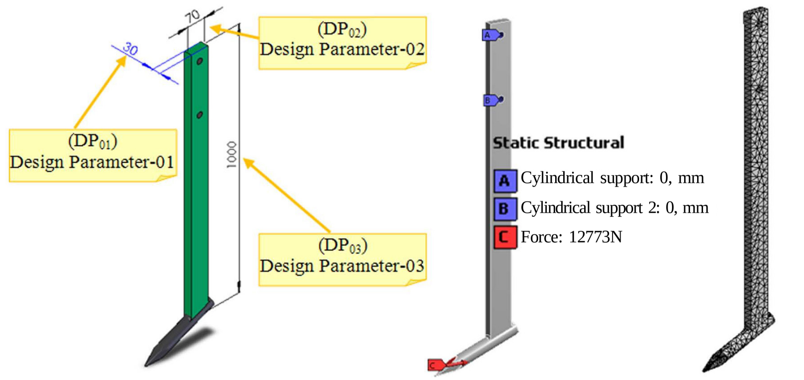


Figure 5. 3D solid model, boundary conditions and mesh structure of the subsoiler tine.

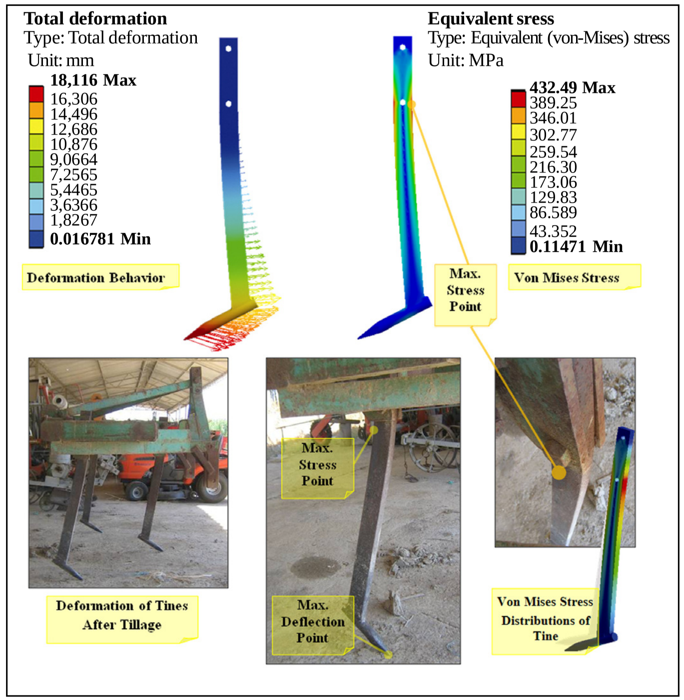


Figure 6. FEM simulation results and deformation of the tine.

used in the meshing operation. Total nodes of 9219 and total elements of 4562 were obtained in the mesh structure of the tine. For the single tine, the solid model, boundary conditions, and mesh structure of the tine are shown, respectively, in Fig. 5.

After pre-processor operations, post process solving procedures were generated for the FEM analysis. According to the simulation results, a maximum equivalent stress of 432.49 MPa and a maximum deflection of 18,116 mm were obtained. The stress results were compared with the yield point (355 MPa) of the tine's material and found that the maximum stress exceeded the yield point, which signified that there was plastic deformation on the tine. Not only the theoretical comparison, but also visual investigations of the tine confirmed that there were deformations on the tine. The FEM simulation prints and deformation pictures are given in Fig. 6.

Optimization of the subsoiler tine: Typically, an element of a machine can work without failure but it doesn't mean that it has best design. Today's competitive industry forces manufacturers to generate the best design for their products. In the context of this paper, this can be defined as an optimization problem and it can be formulated mathematically and solved. Today, computer integrated optimization techniques are used to obtain the best design parameters for products. The mathematical meaning of optimization is obtaining conditions (parameters), which give maximum or minimum magnitude of a function [11]. A design optimization problem is defined with three constituents, which are design parameters (variables), design constraints, and goal functions (objective functions) [12].

Generally, an optimization problem can be defined as follows: To find out the value of $X=\{X_1, X_2, \dots Xp\}$ that ensures as constraints of $g_j(x) \leq 0$, j =1, 2,…m and $h_i(x) = 0$, i = 1, 2,…n which are minimized f(x) function. There f(x) is objective function; gj (x) and hi (x) are design constraints that are equality and inequality; X_1, X_2, … Xp are design parameters (Fig. 7). According to Fig. 7, if point X* is the minimum for f(x) function, that means it is the maximum for -f(x) function.

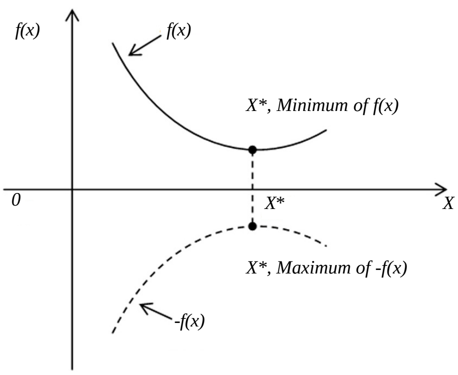


Figure 7. Curve of optimization.

A structural optimization problem can be classified with respect to the type of the structural behaviour, the type of design variables and the type of the structure to be optimized. There are mainly three classes of structural optimization problems: sizing (mass), shape and topology (or layout), depending on the type of the structure to be optimized (Fig. 8) [13].

The following is focused on the structural size optimization of the subsoiler tine. FEM results and visual investigations signified

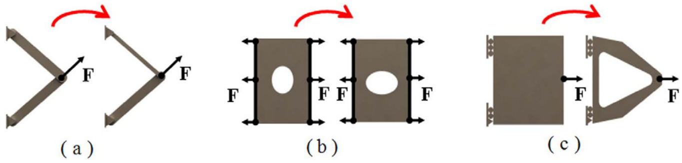


Figure 8. Structural optimization: size (a), shape (b) and topological optimization (c).

that there was plastic deformation. Hence, the objective function was predefined to obtain design parameters for the optimum tine geometry without plastic deformation with possible minimum mass. It means that the stress magnitude must be under the yield point of material. In addition to this, the mass must be the minimum possible to gain the optimum material weight. In the optimization study, not all of the feature dimensions were used. Initial design parameters were assigned as DP_{01} (Design parameter-01), DP_{02} (Design parameter-02) and DP_{03} (Design parameter-03) which have values of 30 mm, 70 mm and 1000 mm, respectively (Fig. 5). Design constraints were assigned for the design parameters as follows:

$$10\,\text{mm} \leq DP_{01} \leq 80\,\text{mm} \tag{1}$$

$$30\,\text{mm} \leq DP_{02} \leq 100\,\text{mm} \tag{2}$$

$$DP_{03} = 1000\,\text{mm (Constant)} \tag{3}$$

The Ansys Workbench DesignXplorer optimization module was utilized for the optimization study. The DesignXplorer environment is a powerful tool for designing and understanding the analysis response of parts and assemblies [14]. A "what-if" parameter study strategy was selected in the optimization module. According to the design constraints, 45 different design sets were created within the module, and then FEM analyses were conducted for all design sets automatically by the module. Response results were set up for equivalent stress (Von Mises), total deformation and total mass of the tine. All of the design sets and variations of the results which are dependent on the design parameters are presented in Table 2. In addition to this, charts that show the relationship between results and design sets are given in Fig. 9-11.

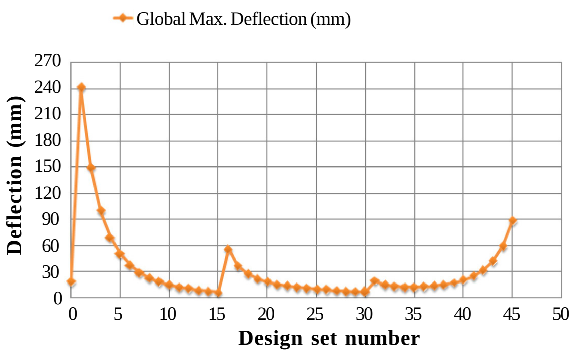


Figure 9. Relationship between global maximum stress and design sets.

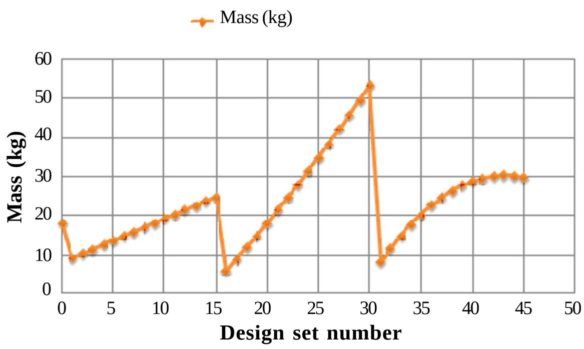


Figure 10. Relationship between global maximum deflection and design sets.

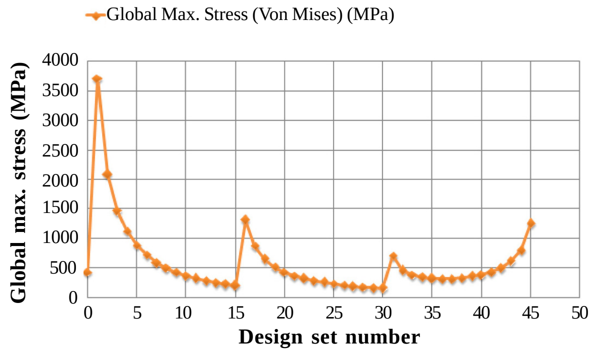


Figure 11. Relationship between tine mass and design sets.

Table 2. Variations of the design sets and results.

Design Sets [Number]	Design Parameter-01 [mm]	Design Parameter-02 [mm]	Mass [kg]	Deflection [mm]	Global Max. Stress (Von Mises) [MPa]	
0	30	70	18.244	18.116	432.490	Initial Design
1	30	30	9.171	240.750	3699.700	
2	30	35	10.313	149.750	2085.700	
3	30	40	11.453	99.612	1463.900	
4	30	45	12.591	69.548	1130.000	
5	30	50	13.726	50.450	890.870	
6	30	55	14.859	37.745	722.420	
7	30	60	15.99	28.959	594.320	
8	30	65	17.118	22.698	500.680	
9	30	70	18.244	18.116	432.492	Derived Initial Design
10	30	75	19.367	14.688	374.290	
11	30	80	20.488	12.069	326.750	
12	30	85	21.607	10.037	287.580	
13	30	90	22.723	8.435	255.340	
14	30	95	23.837	7.156	229.150	
15	30	100	24.949	6.122	206.440	
16	10	70	5.9233	56.263	1308.500	
17	15	70	8.9073	36.934	873.330	
18	20	70	11.955	27.461	648.760	
19	25	70	15.067	21.837	517.150	
20	30	70	18.244	18.115	432.630	Derived Initial Design
21	35	70	21.485	15.474	368.870	
22	40	70	24.79	13.497	324.200	
23	45	70	28.16	11.966	284.780	
24	50	70	31.595	10.740	257.120	
25	55	70	35.094	9.738	231.680	
26	60	70	38.657	8.904	213.020	
27	65	70	42.283	8.198	194.830	
28	70	70	45.974	7.593	179.950	
29	75	70	49.734	7.067	168.410	
30	80	70	53.554	6.608	156.740	
31	10	100	8.1796	19.415	706.860	
32	15	95	11.724	14.744	460.920	
33	20	90	14.955	12.846	385.560	
34	25	85	17.877	12.116	346.610	Approved Final Design
35	30	80	20.488	12.069	326.980	
36	35	75	22.793	12.541	319.120	
37	40	70	24.79	13.497	322.550	
38	45	65	26.483	15.004	335.150	
39	50	60	27.873	17.196	358.020	
40	55	55	28.96	20.338	389.400	
41	60	50	29.745	24.874	441.800	
42	65	45	30.23	31.584	506.360	
43	70	40	30.416	41.909	616.620	
44	75	35	30.311	58.653	802.030	
45	80	30	29.906	88.149	1258.100	

Results and Discussion

According to the objectives of the optimization study, evaluations were generated for all "what-if" study results, then design set number 34 (see Table 2) was agreed as the final design for the tine. The "what-if" study results showed that not only the stress concentration, but also the mass of the tine are reduced, the resultant reduction being 0.367 kg. This means that the mass of the tine was reduced by 2.01%. A comparison of the initial and final design parameters are given in Table 3.

When the use of embedded energy is considered in the manufacture of such equipment, machine weight reduction becomes an important issue for product design as well. The scientific literatures signify that agricultural machines of 1 kg has an equivalent energy of 62.7 MJ [15, 16]. The simulation applications, which are based on 3D modeling, numeric methods and optimization methods are therefore becoming more common place in the product design area, not only for product design time, but also manufacturing costs and energy consumption can be decreased by using these applications. Consequently, the usage of these applications in the agricultural machinery design and manufacturing process will provide important benefits to create optimum designs of the agricultural machineries and costs.

Table 3. Comparison of the initial and final design.

Subsoiler Tine Parameters	Unit	Initial Design	Final Design
Design Parameter-01	[mm]	30	25
Design Parameter-02	[mm]	70	85
Design Parameter-03	[mm]	1000	1000
Equivalent Stress (max.)	[MPa]	432.490	346.610
Global Max. Deflection	[mm]	18.116	12.116
Mass	[kg]	18.244	17.877

Conclusions

This study was focused on the structural optimization of agricultural deep tillage machinery and tools by means of CAE applications. For this purpose, a case study was constructed and presented. A subsoiler which has three tines was used in the case study. According to the study, a number of points can be summarized as follows:

1. Maximum draft force of the subsoiler was calculated as 38.32 kN in the field experiments. This means that each tine has 12.773 kN maximum draft forces.
2. In the FEM stress analysis, the maximum equivalent stress was 432.490 MPa, and a total deflection of 18.116 mm was obtained on the initial design of the tine. When compared with the yield point of the tine material, the results signified that there was plastic deformation occurring on the tine.
3. A "what-if" parameter strategy was used in the optimization study and in total, 45 design sets were created and solved. After consideration of all of the results, design set number 34 was agreed as the optimum design of the tine under the defined conditions.
4. The final design of the tine has maximum global stress of 346.61 MPa and maximum total deflection of 12.116 mm.
5. Total mass of the tine was reduced by 0.367 kg, the equivalent of 2.01%.

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References

[1]McLaughlin, N. B., Lapen, D. R., Kroetsch, D., Wang, X., Gregorich, E. G., Ma, B. L. and Li, Y. X. [online], [Last accessed: 03.07.2009]. Soil compaction and corn roots. Agriculture and Agri-Food Canada, Ottawa, Ontario. Available from URL: http://www.farmwest.com/index.cfm?method=library.showPage&librarypageid=145.

[2]Isik, A., Akinci, I., Kirisci, V., Tuncer, I. K., Karakaya, N. E. and Koksal, R. 1995. Power and energy requirements of vibrated subsoilers. DGGA, Turkish Journal of Agriculture and Forestry. **20**:145-156. (In Turkish).

[3]Özmerzi, A. 2001. Mechanization of garden plants. Akdeniz University Press, Antalya, Turkey, Publication No. 76, 146 p.(In Turkish).

[4]Moaveni, S. 1991. Finite element analysis. Prentice Hall, USA. 510 p.

[5]Gameda, S., Raghavan, G. G. V., Theriault, R. and McKyes, E. 1983. Effect of subsoil compaction on corn production. ASAE Paper No. 83-1043, ASAE, St. Joseph, MI.

[6]Mouazen, A. M. and Nemenyi, M. 1999. Finite element analysis of subsoiler cutting in non-homogeneous sandy loam soil. Soil and Tillage Research. **51**(1-2):1-15.

[7]Zeytinoglu, M. 2002. A research on strength analysis of the curved beam of plow by using finite elements method. Journal of Uludag University, Fac. of Agriculture. **16**(2):169-176.

[8]Değirmencioğlu, A., Çakir, E., Gulsoylu, E. and Kececioglu, G. 1998. Mouldboard plough design modifications using finite element method. 18th National Congress on Agricultural Mechanization, Tekirdag, Turkey. (In Turkish).

[9]Poodt, M. P., Koolen, A. J. and Van der Linden, J. P. 2003. FEM analysis of subsoil reaction on heavy wheel loads with emphasis on soil preconsolidation stress and cohesion. Soil & Tillage Research. **73**:67-76.

[10]Ansys Software Product 2009. Meshing Help. Release 11.0 Documentation for Ansys Workbench.

[11]Rao, S. S. 1996. Engineering optimization-theory and practice. 3rd edn. Purdue University, Indiana, USA.

[12]Akhoroz, E. 1999. Design Optimization with ANSYS FEM Code. MSc. thesis, Dept. of Mechanical Engineering, Istanbul Technical Universty, Istanbul, Turkey. (In Turkish).

[13]Papadrakakis, M., Lagaros, N. D. and Plevris, V. 2004. Structural optimization considering the probabilistic system response. Theoret. Appl. Mech. Belgrade. **31**(3-4):361-393.

[14]Ansys Software Product 2009. DesignXplorer Help. Release 11.0 Documentation for Ansys Workbench.

[15]Singh, J. M. 2002. On farm use pattern in different cropping systems in Haryana, India. Masters thesis (unpublished), International Institute of Management, University of Flensburg, Germany. pp. 118.

[16]De, D., Singh, S. and Chandra, H. 2001. Technological impact an energy consumption in rainfed soybean cultivation in Madhya Pradesh. Applied Energy. **70**:193-213.