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Structural Optimisation of a Subsoiler

Mehmet Topakci[a]*, Huseyin Kursat Celik[a]*, Murad Canakci[a], Davut Karayel[a] and Allan Rennie[b]
[a]Department of Agricultural Machinery, Faculty of Agriculture, Akdeniz University, Antalya, Turkey
[b]Lancaster Product Development Unit, Department of Engineering, Lancaster University, Lancaster, UK

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Abstract. An experimental study of a subsoiler, used for deep tillage in agricultural fields, was carried out to determine its maximum draft force. The working conditions of the subsoiler were simulated three-dimensionally. The simulation showed that a structural optimisation can be generated on a subsoiler framework body for reducing the weight. New design parameters of the framework were defined and finite element analysis gave an optimised redesign for the subsoiler with the framework weight reduced by approximately 27.62%.

Keywords: subsoiler, computer aided design, finite element analysis, structural optimisation, weight reduction

Introduction

Soil compaction, typically caused by heavy wheeling and repetitive tillage in agricultural fields, is an undesired factor. It changes the physical parameters and water infiltration that cause reduction in the crop yield (Akinci *et al.*, 2004a). A hard layer of soil exists about 250 mm under the surface, known as the hardpan (plow pan), which must be cut into smaller pieces because it does not allow vegetation to grow in a healthy manner.

One useful method to avoid negative effects of soil compaction in agricultural fields is deep tillage using a subsoiler (Ozmerzi, 2001), which is a tillage tool that can work up to depths of 450-750 mm under the surface. Manufacturers typically design subsoilers as steel construction, consisting of a main framework, support parts, tine and a narrow share. Additional to the standard subsoiler design, a number of different types of subsoiler designs can be seen in agricultural fields, which are used for a number of varied applications. When working with the subsoiler, its construction is subjected to reaction forces from the soil due to the deep tillage. According to these working conditions, if the construction does not compensate the soil reaction forces, elements of the subsoiler could be subjected to forces that cause deformation. This deformation could cause machinery failure during operation.

It is, therefore, a necessity that force effects and stress distributions should be well described to prevent failure of tillage machines. This information is also extremely important for consideration of the designers and machine manufacturers to consider. Machine manufacturers use particular materials in order to avoid possible errors and failures, which have high safety coefficients or high weight machine elements. Although this prevention would render the equipment safe, the resulting weight and cost of the products will inevitably rise. Many working designs may be operationally sufficient within the defined working conditions, but the ideal aim is to generate an optimal design. Therefore, the use of optimisation techniques is an important application for this area of industry. Software-based integrated numerical techniques and optimisation techniques have been used in machine design procedures since the 1960's. Focusing on machine system optimisation, the need for structural machine element optimisation becomes a requirement. The aim of structural optimisation is to obtain the optimal structure using geometrical, material and topological parameters (Uzun, 2006).

Significant research has been undertaken on subsoilers and their effects on agricultural fields. Among those, Gameda *et al.* (1983) investigated the effect of subsoil compaction on corn production yield under axle load, Isik *et al.* (1993) researched draft force requirement of a prototype single-shank vibrating subsoiler on tillage; Kushwaha and Shen (1995) used finite element method (FEM) to prediet dynamic interaction between the soil and the tillage tool. The researchers indicated that their method could work for predicting the forces acting between the soil and any other kinds of tillage tools by considering some modification. Fielke (1999) investigated the effect of cutting edge geometry of a 400 mm wide experimental sweep on horizontal and vertical components of forces using FEM. Mouazen and Nemenyi (1999) investigated and analysed soil-loosening processes in non-homogeneous sandy loam soil with subsoiler using finite element method (FEM). Degirmencioglu *et al.* (1998) generated a simulation study about the framework of a plough with FEM, investigat-

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*Author for correspondence; E-mail: mtopakci@akdeniz.edu.tr

ing stress distribution and suggested material reduction options. In spite of these numerous studies, which are focused more towards subsoil tillage and subsoiler effects on soil, the subsoiler construction design, stress analysis and subsoiler element optimisation by numerical methods are not yet fully addressed in the scientific literature.

Designing a universal model is an impossible task due to fuzzy conditions of the working environment. Jayasuriya and Salokhe (2001) suggested the use of computer aided method for creating the supporting database of model parameters in order to utilise them for any specific condition or design purpose. Computer integrated design software helps in development of complete system design processes, especially the use of three dimensional (3D) solid modelling and finite element analysis (FEA) applications, now forming a branch of software known as computer aided engineering (CAE). Use of these techniques for the design of agricultural machine systems is inevitable and now a commonplace.

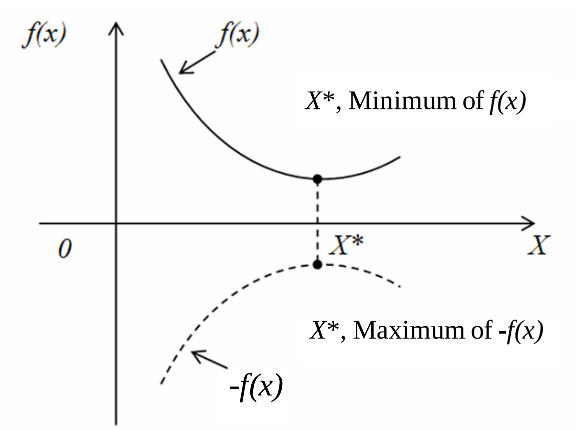
In the present study, focus has been on the optimisation of an existing tillage tool. FEA, 3D solid modelling and structural optimisation were carried out for a sample subsoiler, which was manufactured by a local company in Turkey. The aim of the study is to obtain optimised design parameters of the subsoiler framework body with possible minimum material weight. To achieve this, advanced CAE techniques were used and the objective function has been defined as minimising material weight by considering defined design constraints in the optimisation study.

Materials and Methods

Optimisation overview. Mathematical definition of optimisation is obtaining conditions, which give the maximum or minimum magnitude of a function (Rao, 1996). Three values are required to define the design optimisation problem: design parameters (variables), design constraints and goal (objective) function (Akhoroz, 1999). Generally, an optimisation problem can be defined as:

Finding out the value of $X=\{X_1, X_2, ...X_p\}$ that ensure as constraints of $g_j(x) \leq 0$, $j = 1,2, ...m$ and $h_i(x) = 0$, $i = 1,2,....n$ which are minimised f(x) function, where: f(x) is objective function, $g_j(x)$ and $h_i(x)$ are design constraints that are equality and inequality, $X_1, X_2, ... X_p$ are design parameters (Fig. 1). According to Fig. 1, if point X* is minimum for f(x) function, it means it is maximum for -f(x) function.

In engineering terms, the definition of optimisation is the act of obtaining the best results under given circumstances (Optimising Design Topology Software, 2005). There are many deciding factors in engineering design processes, such as minimising costs and weight of a product whilst maximising profit and yield. If these factors are defined as a function of specific variables, that could become an optimum design problem. However, different optimisation methods have been developed for different optimisation problems. Structural optimisation is defined through three categories: (a) mass optimisation (design optimisation), (b) shape optimisation and (c) topological optimisation (Fig. 2) (Haubler *et al.*, 2001).



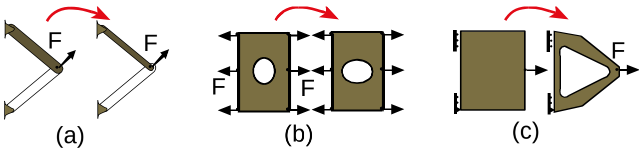


Fig. 2. Structural optimisation family, (a) mass, (b) shape, (c) topological optimisation.

Topology optimisation is a method of determining the optimum material distribution (shape) over a prescribed design space (area or volume) meeting a set of objective functions. From a block of material, the structural shape can be optimized for optimal stiffness at a minimum weight for a given loading environment. The purpose of structural shaping optimisation analysis is to find the best use of material for a body. Typically, this involves optimising the distribution of material, such that a structure will have the maximum stiffness for a defined set of loads. Many different objective functions need to be considered simultaneously for different load conditions and constraints to produce an optimum geometry. In addition, the optimum shape may change based on the material selection process. Therefore, topology optimisation can be used to optimise the geometry for the purposes of weight reduction, minimising material requirements or selecting cost effective materials and analysing composite material characteristics that deliver the optimal mechanical performance based on the design concepts. Topology optimisation can be used to determine initial design concepts but can also be used to refine existing structural components and systems. This leads to a analysis of highly efficient initial product design concept in less time, resulting in a higher quality product with lower overall development costs (Rao, 1996).

The present study is focused on the structural optimisation of the subsoiler framework, through using FEM based topology optimisation techniques. Every finite element-based model, that is intended to be optimised in the sense of topology optimisation, needs a set of imposed loads and boundary conditions. The optimisation, then, leads to an improved model with respect to the loads and boundary conditions, defined previously. The optimisation itself is an iterative procedure where the geometrical structure of the body is changed until a user defined objective is met. This definition is given in Fig. 3 as a basic optimisation process flow (Akhoroz, 1999).

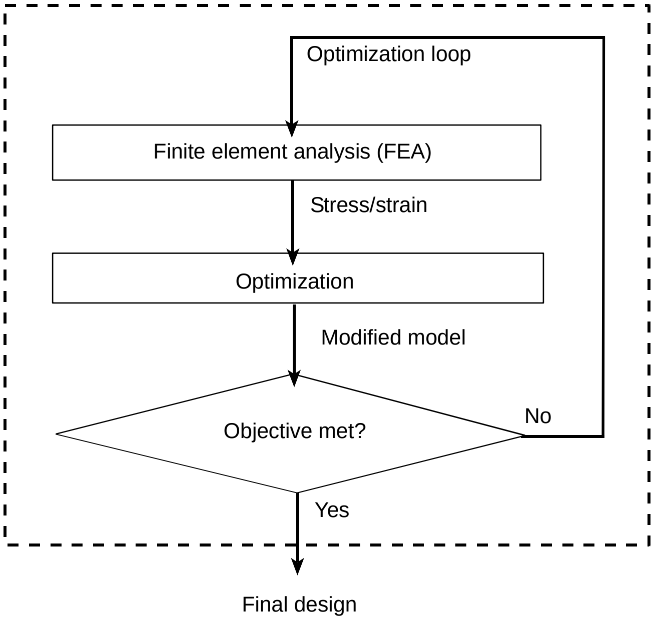
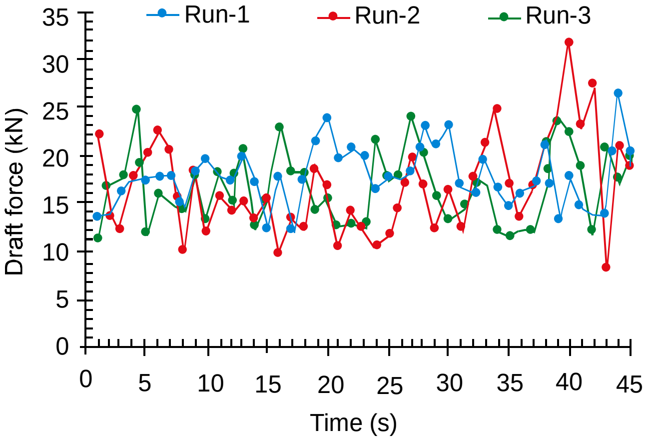


Fig. 3. Basic optimisation process.

Determination of draft forces for subsoiler. Draft forces affect the subsoiler on tillage, directly. An experimental study was realized to determine draft forces by two-tractor method with a dynamometer for subsoiler. HBM-U9A dynamometer was used for measuring the implement force. The force transducer had a nominal force of 50 kN and a nominal sensitivity of 1.1 mV/V, the sensitivity tolerances being within ±0.5% of pull force. Nominal range of supply voltage was 0.5 to 12V and that of temperature was -10 to 70 °C. The mass of force dynamometer was 400 g (Akinci *et al.*, 2004b). In the agricultural field, where the experimental study was carried out, the soil structure comprised of sand (15%), clay (30%) and silt (55%). Average moisture content of the soil was 4.5% (d.b.) for dry condition. Maximum draft force magnitudes were obtained by the experimental study. A series of three identical runs were conducted during the experimental study. Values were recorded throughout 45 sec., for each run, measured in millivolt (mV) and then converted to kilonewton (kN). According to these variables, the maximum draft force value was determined as 32.01 kN based on the peak force experienced in run-2 (Fig. 4).

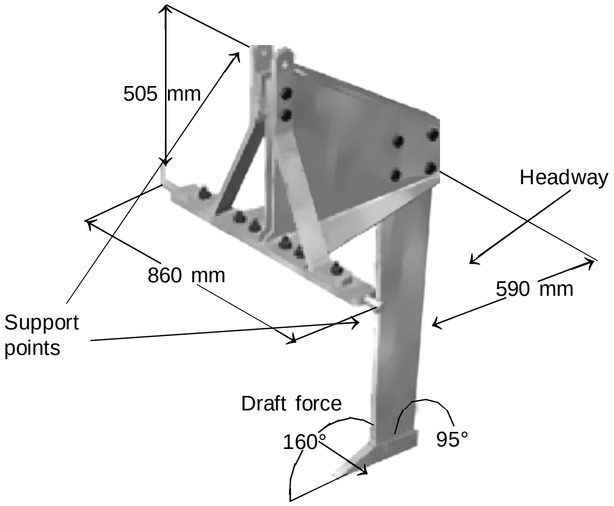


Draft force (kN)	Average	Max.	Min
Run-1	17.78	26.72	12.21
Run-2	16.81	32.01	8.48
Run-3	16.83	25.07	11.70

Fig. 4. Experimental data for draft force of subsoiler.

Finite element analysis of subsoiler. In this part of the study, FEA was carried out to investigate stress distributions on the subsoiler, which was subsequently manufactured by a local commercial company. FEA was set up in 3D, linear, static and isotropic material model assumptions. The subsoiler was prepared as a 3D solid model and ansys workbench commercial FEA code was used for the strength analysis. All subsoiler elements and bolt connectors were used in the 3D solid model assembly of the subsoiler that was generated by solid works parametric 3D design software. (Fig. 5).

Working conditions were set up in the FEA software to simulate the act of the subsoiler under maximum draft force on tillage. The subsoiler was supported at the tractors three-point linkage and maximum draft force was applied to the surface of the narrow share as 32.01 kN through opposite of headway. The narrow share had a 20° tangent. Construction steel



Material properties of construction elements (St 52)		
Young's modulus	[GPa]	205
Tensile ultimate strength	[MPa]	520
Yield strength	[MPa]	355
Poisson ratio	[-]	0.29
Density	[kg/m^3]	7870
Bolt connections	[Standards]	8.8

Fig. 5. 3D solid model of the subsoiler, boundary conditions and material properties of the construction elements.

(St52) was assumed as the material of the subsoiler. Boundary conditions and properties of the material are presented in Fig. 5.

The finite element model was obtained in the analysis procedure. Finite element model operations were generated using the meshing function oF ANSYS workbench (ANSYS, 2007). The finite element model obtained had a total of 74430 nodes and a total of 84176 elements.

After running the FEA process, stress distributions were obtained on the construction of the subsoiler. In the FEA post-process function, an output screen was displayed, which detailed that the maximum equivalent stress (Von Misses) occurred on tine as 324.6 MPa (Fig. 6). Plastic deformation and failure were not seen when the maximum stress magnitude was evaluated according to the yield stress point of the material. The construction was acting in the elastic region of the material's stress-strain curve.

Optimisation of framework. If stress distributions are investigated for the main body of the framework, it can be seen that the maximum equivalent stress occurred as 267.21 MPa. This value is also below the yield stress point of the material of the body. No plastic deformation was observed; however, if safety factors are accounted for, the results show that the body has a high safety coefficient on most of its region. This means that, the body is working under the low loading value in the

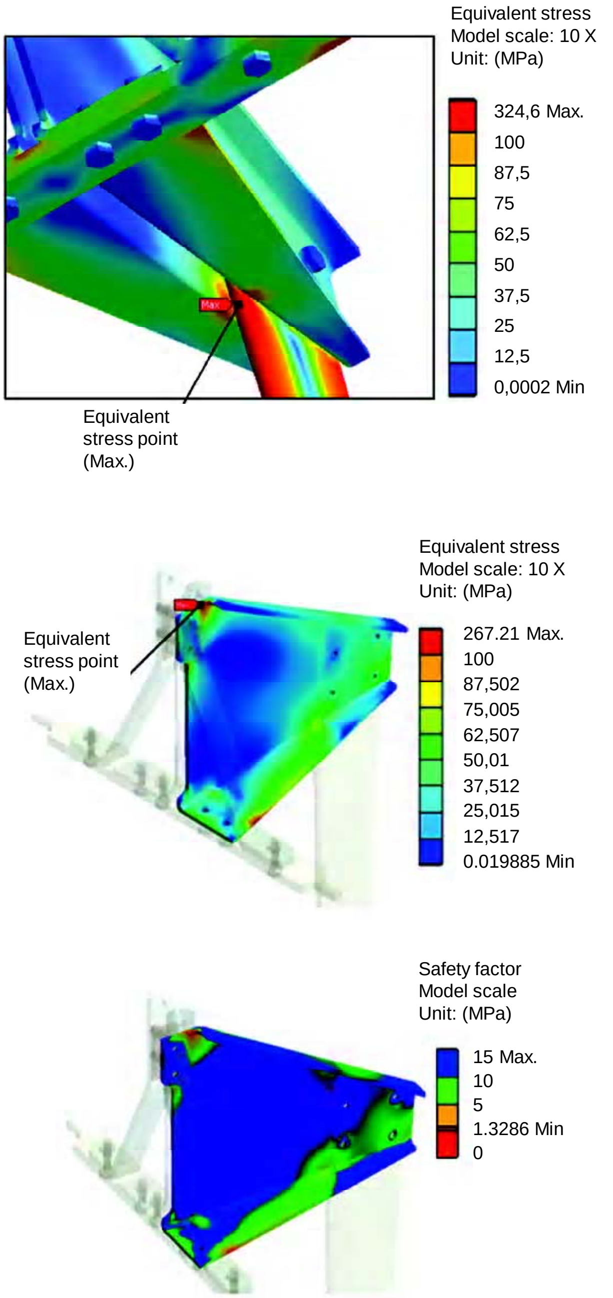


Fig. 6. Finite element analysis result: Equivalent stress distribution (Von Misses) of the framework main body and its safety factors.

region that has a high safety coefficient; hence, these regions are irrelevant for loading. The safety factor was determined according to the yield stress point of the material by the software. According to the FEA results, safety working factors were calculated for the entire constructions. The maximum safety factor of 15 was calculated, as shown in Fig. 6.

According to the evaluation, reducing the body weight was defined as an objective function. The shape finder module of ANSYS workbench was used to generate optimisation (Fig. 7). The reduction level of the body was determined by the shape finder module. All design constraints of the body were evaluated and new parameters of geometry were defined according to the optimisation study result. Additionally, paired samples t-test was used to compare initial design and final design values of equivalent stress and weight of the frameworks body. Outputs of the optimisation study and the new geometry of the body can be seen in Fig. 8.

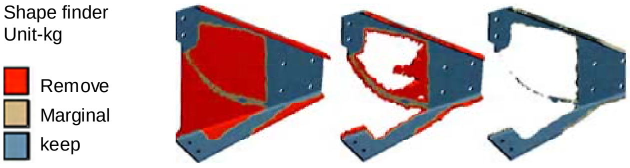


Fig. 7. Shape finder operation.

Results and Discussion

Finally, optimal parameters were chosen for the final design and FEA was regenerated for the subsoiler. The maximum equivalent stress value was measured as 326.23 MPa (Fig. 8). It can be seen that if stress results of the final design were compared with initial design results, the maximum equivalent stress value increased, but it was still within the yield stress value of the construction material. Hence, the final design works without any failure.

Table 1. Comparison between the initial design, and the final design

Framework body of subsoiler	Initial design	Final design	(%)
Equivalent stress (max.) [MPa]	267.210	326.230	18.08 (increase)
Weight [kg]	41.417	29.978	27.62 (reduction)

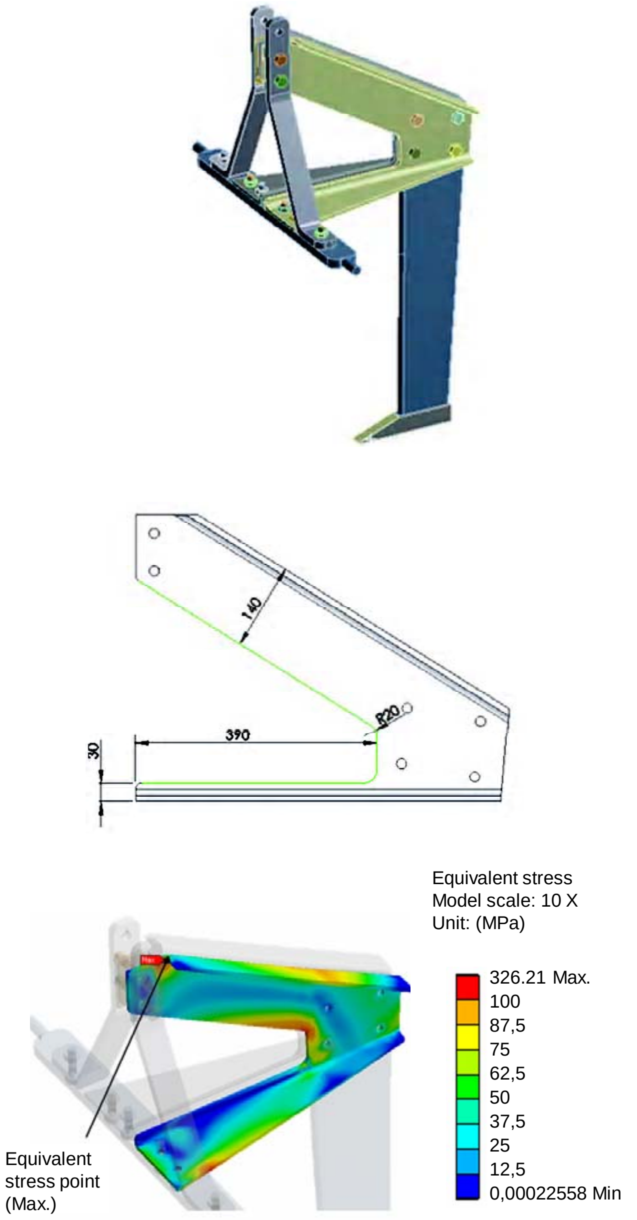


Fig. 8. Defined new geometry of body and its stress distribution.

As a result of this, the frame work body weight reduced by 11.439 kg. A comparison of the values between the initial and the final designs are given in Table 1. Differences between the initial and the final design values of equivalent stress and weight of the framework body of the subsoiler was statistically significant ($P<0.05$). While the equivalent stress of the subsoiler's final design was significantly higher than its initial design, the weight of the subsoiler's final design was significantly lower than its initial design.

The main consideration in the present study was the achievement of optimum topology and shape of the framework body under defined boundary conditions by considering the design constraints. One of the constraints had been maintaining the maximum equivalent stress value under the yield point (355 MPa) of the material. Additionally, geometrical constraints were considered while creating the final geometry of the framework body so as not to create any subsequent problems in the assembly of other subsoiler elements.

In fact, for a total new design process of a tillage tool, three different characteristics must be taken into consideration for the modelling of the soil tillage process, namely: the soil material behaviour, soil-tillage tool interaction, and the material behaviour of tillage tool itself (Mouazen and Nemenyi, 2000). In this study, no change was made to the subsoiler tine which could affect soil and soil-tool interaction behaviour issues. Hence, just the tillage tool structural optimization issue was taken into consideration without behaviour of the soil and soil-tool interaction or draft force minimisation issues.

Conclusion

In this paper, a structural optimisation study was carried out for a subsoiler's framework body. In addition, it was focused that the design of the tillage tool could become faster, more efficient and reliable through the use of CAE applications and optimisation techniques which were integrated in the software. In the first place, the initial design was evaluated by 3D FEA. The FEA results showed that an optimisation study could be generated for the framework body. In the study, the objective function was defined as reducing the weight of the body and design constraints defined as yield stress point of material. According to the optimisation study, new geometrical parameters were defined and the FEA was regenerated. In the FEA of the final design, maximum stress value increased by 18.08% but this rise is not significant for any failure. This means that final design of the subsoiler is suitable without failure in the defined condition. Consequently, the framework body weight of the subsoiler was reduced by 27.62%. This profitable reduction of weight is quite significant, and will affect the yield of tillage parameters. In addition, it is a beneficial gain that costs are reduced by using the optimal design, developing design processes and competition for manufacturers specifically operating in the agriculture industry sector.

Additionally, reduction in machine weight decreases usage of embodied energy. It has been stated that the equivalent energy per kg of the agricultural machine was 62.7 mega joule (MJ) (Singh, 2002; De *et al.,* 2001). Usage of CAE applications and optimisation techniques for machines will provide a reduction in the consumption of energy and use of excessive material. Thus, it can be concluded that the application of these new techniques help energy conservation together with the other advantages stated.

Acknowledgement

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References

Akinci, I., Cakir, E., Topakci, M., Canakci, M., Inan, O. 2004a. The effect of subsoiling on soil resistance and cotton yield. *Soil And Tillage Research,* **77:** 203-210.

Akinci, I., Canakci, M., Topakci, M., Ozmerzi, A., Yilmaz, D. 2004b. Development of draft and torque measurement system for agricultural machinery, *Energy Efficiency and Agricultural Engineering Conference*, pp. 308-314, Rousse, Bulgaria.

Akhoroz, E. 1999. Design Optimization with Ansys FEM Code. *M.Sc. Thesis*, Istanbul Technical University, Ýstanbul, Turkey.

ANSYS, 2007. Release 11 Documentation for ANSYS Workbench.

De D., Singh, R.S., Chandra, H. 2001. Technological impact on energy consumption in rainfed soybean cultivation in Madhya Pradesh. *Applied Energy*, **70:** 193-213.

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

Fielk, J.M. 1999. Finite element modelling of the interaction of the cutting edge of tillage implements with soil. *Journal of Agricultural Engineering Research,* **74:** 91-101.

Gameda, S., Raghavan, G.S.V., Theriault, R., McKyes, E. 1983. Effect of Subsoil Compaction on Corn Production. *Paper presented at 1983 Summer Meeting of the American Society of Agricultural Engineers,* St. Joseph, Michigan 49085, USA.

Haubler, P., Emmrich, D., Müller, O., Ilzhöfer, B., Nowicki, L., Albers, A. 2001. Automated Topology Optimization of Flexible Components in Hybrid Finite Element Multibody Systems Using ADAMS/Flex. and MSc. construct. *16th European ADAMS User's Conference,* Institute of Machine Design, University of Karlsruhe, Germany.

Isik, A., Tuncer, I.K., Akinci, I., Karakaya, N.E. 1993. The Prototype of Single-Shank Vibrating Subsoiler and its Drawbar Power Requirement. *5th International Congress on Mechanization and Energy in Agiruculture,* pp. 141-150, Izmir, Turkey, (In Turkish).

Jayasuriya, H.P.W., Salokhe, V.M. 2001. Review Paper. A review of soil-tine models for a range of soil conditions. *Journal of Agricultural Engineering Research,* **79:** 1-13.

Kushwaha, R.L., Shen, J. 1995. Finite element analysis of the dynamic interaction between soil and tillage tool. *Transactions of the American Society of Agricultural and Biological Engineers* (ASABE), **38:** 1315-1319.

Mouazen, A.M., Nemenyi, M. 2000. Finite element modeling of subsoiling processes. *Advances in GeoEcology,* **32:** 126-134.

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

Optimizing Design Topology Using Your Finite Element Models, 2005. MSc Software Corporation Product overview [MSC], [online, available from URL: http://ww.mscsoftwar.com/assets/3154 _NA2004 NOVZTOP-ZLTDAT. pdf [Last accessed 20.11.2007].

Ozmerzi, A. 2001. *Mechanization of Garden Plants,* Publish Number: 76, 146 pp., Akdeniz University Press, Antalya, Turkey (in Turkish).

Rao, S.S. 1996. *Engineering Optimization-Theory and Practice,* 3rd edition, John Wiley and Sons Inc., New York, USA.

Singh, J.M. 2002. On Farm Energy Use Pattern in Different Cropping Systems in Haryana, India. *M.Sc. Thesis,* International Institute of Management, University of Flensburg, Germany.

Uzun, Y.H.I. 2006. Optimization Techniques in Mechanical Engineering. *M.Sc. Thesis,* Yildiz Technical University, Istanbul, Turkey (in Turkish).