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Relationship between different parameters of an inclined subsoiler

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ABSTRACT

Subsoilers are agricultural implements used to break the hardpans below the tillage depth. Minimizing the subsoiler weight without compromising the subsoiler safety is one of the leading design objectives. The thickness of shank, length of curve and width of shank are critical parameters in the design process. Maximizing the structural safety and minimizing the weight are achieved by determining the significance of the geometrical parameters. This paper deals with the correlation between an inclined subsoiler's input and output parameters. The parameters correlation was carried out to determine the extent of relationship between different parameters and the sensitivities of the input parameters with respect to the output parameters. The parameters correlation tool of ANSYS Workbench was used for the analysis. The results of the parameters correlation indicated that thickness of shank and width of shank had significant effects on the output parameters while the effect of length of curve of the inclined subsoiler was not significant. Thickness of shank had the highest relevance with the inclined subsoiler mass having a correlation value of 0.8849 and an R^2 contribution of 0.7554. Width of shank had the highest relevance with maximum total deformation with a correlation value of -0.7899 and an R^2 contribution of 0.6133. Inclined subsoiler mass, safety factor and inclined subsoiler volume exhibited increasing trends both linearly and quadratically with the increase in thickness and width of shank. On the other han, total deformation equivalent and maximum principal stress exhibited decreasing trends.

Keywords: Parameters correlation; correlation analysis; ANSYS; finite element modeling

INTRODUCTION

Tillage is critical in agricultural production. It helps in effectively removing weeds, preparing an appropriate seedbed and promoting air and water movement in the soil (Hamzei and Seyyedi 2016). Globally the compaction of agricultural soils is a significant issue for crop productivity and the environment (Lipiec and Hatano 2003). Soil compaction occurs because of the imbalance between the various forces exerted by soil tillage or wheel traffic and the bearing capacity of the soil (Nevens and Reheul 2003). The immediate outcomes of increased soil compaction are impaired root development and root function. It is induced by reduced aeration and higher soil mechanical resistance (Tardieu 1994).

Plant roots in compacted soils have lesser lengths compared to the non-compacted soils. The root system develops superficially leading the root to explore a smaller soil area and absorb a limited amount of nutrients and water (Boone et al 1987, Hakansson and Lipiec 2000). Further compaction of the soil reduces the soil's microbial biomass and enzyme activity (Nawaz et al 2013). Mineralization suffers as a consequence (De Neve and Hofman 2000). Denitrification rates in compacted soils are also significantly higher than those in non-compacted soils (Ball et al 1999).

Subsoiling is specifically suitable for shattering the compacted soil layer in agricultural fields (Mouazen and Ramon 2002). Existing soil compaction is removed in subsoiling and soil rooting depth is not reduced

(Carter 1988). Tractor-driven subsoilers are usually used to breakup the hardpan layer beneath the topsoil layer by subsoiling to a depth of 30 to 50 cm. The drainage is improved; so the water moves downward and penetrates deeper promoting root growth (Gajri et al 1997, Singh et al 2019). On silty loam soils, annual subsoiling led to a 4.9 per cent reduction in bulk density compared to no-till control plots (Jin et al 2007). Subsoiled soils showed a significant improvement in infiltration rate compared to control plots (Soltanabadi et al 2009).

Approximately half of all crop production energy is consumed by tillage practices (Kushwaha and Zhang 1998). Energy efficiency can be improved by optimizing tillage tool design. It is vital to model soil-implement interaction accurately to optimize the tool, eliminating the need for many expensive field tests and reducing the time for prototype development and verification (Shmulevich et al 2007).

One of the primary steps for the optimization process is to accurately identify the effect of various design parameters of the tillage tool on the various forces acting within the tool. Computer algorithms and mathematical methods developed to optimize tillage tools can determine how various tool parameters affect the tool's reliability and performance (Rucins and Vilde 2005). Several statistical measures can determine the connection between the various tillage tool parameters. One of the most common is correlation analysis (Abo-Alkheer et al 2011).

The current study was undertaken to determine the relationship between the different parameters of the inclined subsoiler using the parametric correlation system in the ANSYS software. Determining the extent of the relationship of each input variable with the outputs is essential. Parameters with minimum relationships lead to unnecessary delays in the processing time. If identified and filtered out early, such parameters lead to better processing time. The parametric correlation evaluates the effect of each input parameter on the design. It also measures the linearity or quadraticity of the relationships (Yildirim et al 2015).

Subsoilers are tractor-mounted equipment developed to loosen and break up the soil below the depth of a traditional disk plow, moldboard plow, chisel plow or rotary plow (Odey and Manuva 2018). Unverferth Company estimates that agricultural subsoilers can disturb hardpan ground to a depth of 60 cm (Mollazade et al 2010). Subsoilers do best in hard soils that lack adequate root penetration and moisture distribution. If the soil texture is uniform up to the depth of subsoiling or if it is too wet, subsoiling is usually less effective (Odey and Manuva 2018). The work conditions of subsoilers are challenging, so they are subject to heavy dynamic loads. Proper design of these machines increases their lifespan and reduces farming costs (Mollazade et al 2010).

Subsoilers come in two basic types: one type is a single standard and another is more than one standard. One standard subsoiler is typically used when a deeper operation is carried out. Multiple standard subsoilers are used for shallower operations. Both trailing and mounting units are available. Subsoilers mainly consist of the following:

Shank or standard: It is the unit's main component. It is vertical or curved toward the front and may have several holes to attach wings or sweeps.

Beam or toolbar: Standard tops are fastened to a beam constructed from a straight flat iron. The joint is made with gusset plates and bolts or rivets. Other standards are fastened to a toolbar behind the tractor's rear wheels. Toolbars can be raised and lowered from the tractor.

Tooth or share: There is a tooth or share at the bottom of the shank. Most subsoilers have a steel point that is reversible when worn.

Model building

SolidWorks software was initially used for modelling the inclined subsoiler. It is a parametric feature and history-based 3D CAD programme. The programme enables designers to generate detailed drawings and models from ideas and experiments with varying dimensions and features. A SolidWorks model consists of three-dimensional geometry that specifies edges, faces and surfaces. One of the most powerful features of SolidWorks is the ability to update all assemblies and drawings when a part is updated (Lombard 2013). Modelling is done as per the specifications of the subsoiler available at the local level. The specifications of the inclined subsoiler are given in material properties (Table 1). Material properties dictate the response of a part under different conditions (Koshal 1993). Hot-rolled structural steel is used for the subsoiler. Table 2 represents the properties of hot-rolled structural steel.

Table 1. Specifications of the inclined subsoiler

Part	Parameter	Value	Unit
Shank	Length	651	mm
	Width	90	mm
	Thickness	25	mm
	Shank angle	75	°
Bottom	Length	432	mm
	Width	80	mm
	Thickness	25	mm
Reversible blade	Length	259	mm
	Width	50	mm
	Rake angle	35	°

Table 2. Material properties of hot rolled structural steel

Material property	Value	Unit
Density	7.87	g/cc
Poisson ratio	0.29	-
Young's modulus	2,05,000.00	MPa
Tensile ultimate strength	420.00	MPa

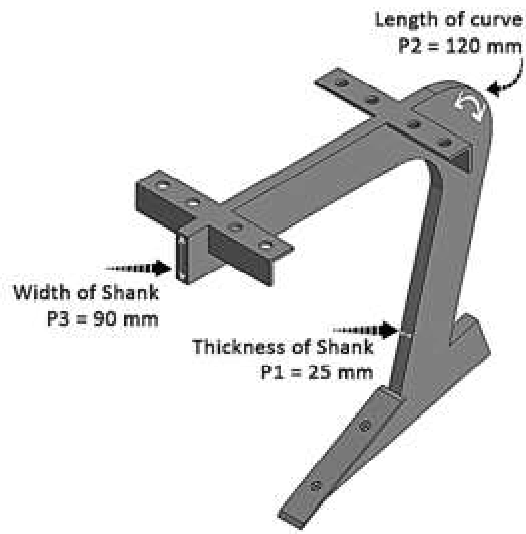

Fig 1. Design parameters of inclined subsoiler

MATERIAL and METHODS

Parametric correlation

The static structural analysis system of ANSYS was used to determine the stresses and strains acting on the subsoiler. Responses were assumed to occur under steady loading conditions. 3D geometry was attached to the structural analysis in ANSYS and engineering properties were applied. The results from the structural analysis were used for the generation of the parameter set containing the input and output parameters.

The input parameters included thickness of shank (P1), length of curve (P2) and width of shank (P3) having values 25, 120 and 90 mm respectively (Fig 1). Output parameters included inclined subsoiler mass (P4), total deformation (P5), equivalent stress (P6), maximum principal stress (P7), safety factor (P8) and inclined subsoiler volume (P9).

Correlation, also called correlation analysis, is a term used to denote the association or relationship between two (or more) quantitative variables. The analysis is based on the assumption that the quantitative variables are linearly related. The measure measures how strong an association is and the association's direction between the variables (Gogtay and Thatte 2017).

Correlation analysis followed the generation of the parameter set. ANSYS has a built-in function for correlation analysis. The parameters correlation function of ANSYS was used for the analysis (Fig 2).

ANSYS lets the user choose the type of correlation, the number of samples for the parameters correlation and the size of the generated sample sets for the correlation statistics among many other options. The end result of a correlation coefficient is the correlation coefficient.

Results from the correlation analysis help classify the input parameters as major and minor parameters. Major parameters affect the output significantly while the minor parameters have negligible effects on the output parameters. Correlation analysis in ANSYS helps filter out the minor input parameters. Minor parameters lead to higher processing times without significantly affecting the output parameters. Hence they need to be excluded from the subsequent processes. One hundred sample points were generated using the model geometry by varying the input variables P1, P2 and P3 by specifying each input variable's lower and upper bounds separately. Pearson's correlation coefficient was calculated between the input and output parameters with the size of the generated sample set for correlation statistics set to 40. The lower and upper bounds assigned for the input parameters for parametric correlation are given in Table 3.

The sensitivity analysis for each input with the output variable was also conducted in addition to the

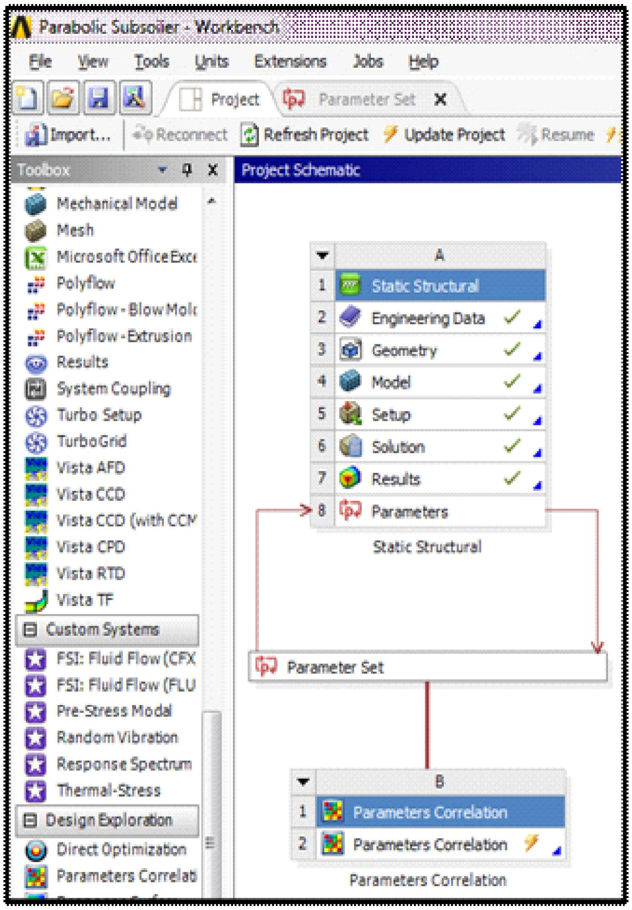

Fig 2. Parametric correlation system in ANSYS

correlation coefficient. Sensitivity analysis is used in numerical models to determine whether the uncertainties in one or more input variables could lead to uncertainty in the output variables. The analysis improves or reduces the model's prediction by analyzing qualitatively or quantitatively the model's response to changes in input variables or by understanding how variables interact with each other (Pichery 2014). The sensitivity analysis was followed by determining the linear and quadratic relationships between the input and output variables using linear and quadratic regression. Regression is one of the most commonly used statistical techniques today. The relationship between a normally distributed dependent variable, Y and a continuous independent variable, X is examined in simple linear regression. The general equation of the linear relationship of Y and X is given by Forthofer et al (2007):

$$Y = aX + c$$

where Y= Dependent variable, X= Independent variable, c= Intercept, a = Coefficient of the independent variable

Table 3. Lower and upper bounds of the input parameters

Parameter	Lower bound	Upper bound
Thickness of shank (P1)	20 mm	25 mm
Length of curve (P2)	110 mm	130 mm
Width of shank (P3)	80 mm	100 mm

Quadratic regression evaluates the best fit for a data set shaped like a parabola. Quadratic regression is the extension of simple linear regression. The general equation of a quadratic relationship of Y and X is given by Banks and Fienberg 2003):

$$Y = aX^2 + bX = c, \text{ here } a = 0$$

where Y= Dependent variable, X= Independent variable, c= Intercept, a = Coefficient of X^2, b= Coefficient of X

Comparison

After classifying the input parameters as major and minor, different combinations of the input parameters were used to fit the regression curves to the output parameters. The R^2 values were obtained for each combination and the conclusions were drawn. The combinations of the input parameters for the analysis were I: P1, P2 and P3, II: P1 and P3, III: P1 and P2 and IV: P2 and P3

RESULTS and DISCUSSION

A force of 7,288 N (Allaie et al 2020) was applied across the subsoiler blade while restricting the subsoiler movement by fixing the holes (Fig 3) and the structural analysis was carried out (Table 4).

Input and output parameters were exported to a parameter set and their correlation analysis was carried out. The end result of correlation analysis is the correlation coefficient. Correlation coefficients of the output parameters with the input parameters are given in Table 5.

Correlation coefficients ranged from -1 to 1. If two variables have a correlation coefficient of +1, they are positively related; if they have a correlation coefficient of -1, they are negatively related. When the correlation coefficient is zero, there is no linear relationship between the two variables (Gogtay and Thatte 2017).

P1 had a significant effect on P4, P5 and P9 with the correlation coefficients being 0.8849, -0.6160 and 0.8849 respectively. The relationship between P1 and P9 was positive indicating that increasing P1 will increase P4 and P9. On the other hand the relationship of P1 with P5 was negative. This implies that increasing P1 will decrease P5. Since P1 significantly affects some of the output parameters, it was considered a major parameter.

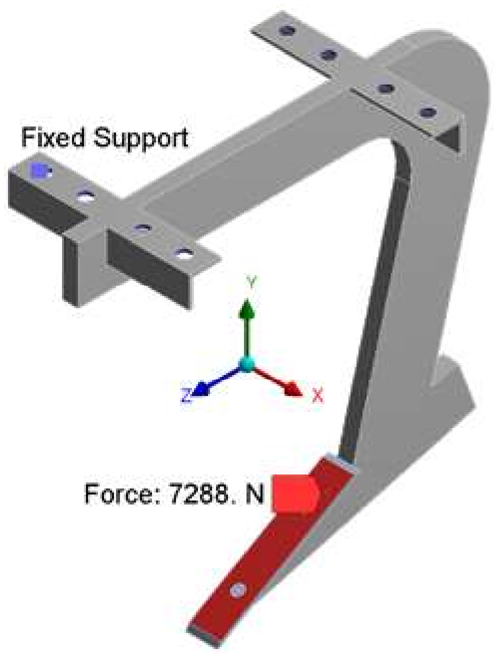

Fig 3. Force and constraints on the inclined subsoiler

Table 4. Results of structural analysis

Parameter	Value
Nodes	55,243
Elements	29,658
Mass	25.89 kg
Volume	32,89,249.89 mm^3
Maximum total deformation	2.7195 mm
Maximum equivalent stress	220.77 MPa
Maximum principal stress	239.93 MPa
Minimum factor of safety	1.585

Table 5. Correlation between the input and output parameters

Parameter	P4	P5	P6	P7	P8	P9
P1	0.8849	-0.6160	-0.3867	-0.4129	0.3689	0.8849
P2	-0.0035	-0.0089	-0.0472	-0.1075	0.0538	-0.0035
P3	0.4724	-0.7899	-0.6795	-0.8263	0.7306	0.4724

The relationship between P2 and the output parameters is very weak with approximately zero correlation coefficient. P2 was therefore considered a minor parameter. The effect of P3 was considerable on all the output parameters. The correlation coefficients of P3 with P5, P7 and P8 were -0.7899, 0.8263 and 0.7306 respectively. P5 and P7 were negatively correlated to P3 indicating that increasing P3 will decrease their magnitude. P8 had a positive correlation with P3. Increasing P3 will increase P8. Since P3 significantly affected some of the output parameters it was also considered the major input parameter during the correlation analysis.

The summary of the parameters correlation is shown in Fig 4. P1 and P3 are the major input parameters. The highest relevance (1.00) of P1 was with P4 with a correlation value of 0.8849 and an R^2 contribution of 0.7554. P3 had the highest relevance (1.00) with P5 with a correlation value of -0.7899 and an R^2 contribution of 0.6133. P2 was the minor input parameter with the highest relevance of 0.4043 with P6. The correlation value of P2 with P6 was -0.07973 and the R^2 contribution of 0.0287.

The sensitivities between the input and output parameters are shown in Fig 5. Sensitivity analysis identifies priority areas for improving knowledge. To perform sensitivity analysis, partial derivatives of the output functions are computed for the input variables (Pichery 2014). The value of sensitivities ranged between -1 and +1. Positive values indicate that increasing the independent variable will cause the dependent variable to increase, while negative values indicate that increasing the independent variable will cause the dependent variable to decrease. Zero sensitivity implies that varying the input variable will not affect the output variable. P1 and P3 had both positive or negative effects on the output parameters but the effect of P2 on the output parameters was zero.

Linear and graphical relationships between the input and output variables were also obtained. Each

Major Input Parameters				
Input Parameter	Best Relationship With Filtering Output Parameter			
	Relevance	Output Parameter	R2 Contribution	Correlation Value
P1 - Thickness of Shank	1	P4 - Inclined Subsoiler Mass	0.7554	0.88491
P3 - Width of Shank	1	P5 - Total Deformation	0.61337	-0.78998
Minor Input Parameters				
Input Parameter	Best Relationship With Filtering Output Parameter			
	Relevance	Output Parameter	R2 Contribution	Correlation Value
P2 - Length of Curve	0.40439	P6 - Equivalent Stress	0.028741	-0.079737

Fig 4. Summary of parameters correlation in ANSYS

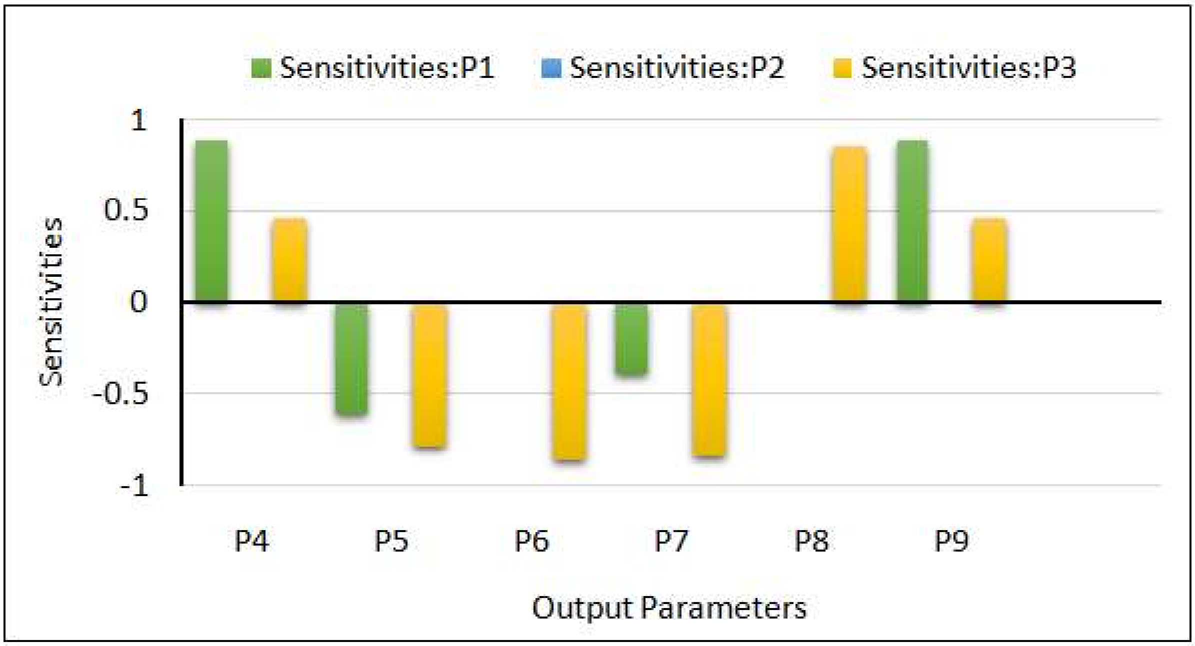

Fig 5. Sensitivities between input and output parameters

input variable was analyzed to study its effect on the output variable. Along with the relationships, the linear and quadratic trends of the different variables with changes in the input parameters were also obtained.

The linear and quadratic relationships between P1 and the output variables are shown in Fig 6 alongwith the equations and R^2. The variation of each output parameter with changes in the input parameter P1 was represented both linearly and polynomially.

The maximum correlation of P1 was found with P4 and the linear and quadratic equations for the relationship are:

Linear: $y= 0.9219x + 2.8544$; $R^2= 78.306\%$

Quadratic: $y= -0.0073819x^2 + 1.2549x - 0.8849$; $R^2= 78.314\%$

where y= P4 (inclinded subsoiler mass in kg), x= P1 (thickness of shank in mm)

P4, P8 and P9 showed increasing trends both linearly and quadratically. On the other hand, P5, P6 and P7 displayed decreasing trends. It was also observed that the quadratic equations showed better relationships compared to the linear equations with better R^2 values for all the output parameters.

The correlation between P2 and the output parameters was poor and as such no significant relationship between the input and output parameters could be established. The linear and quadratic relationships between P2 and the output parameters are shown in Fig 7. There was minimal variation in the output parameters with changes in the input parameter. The R^2 value between the input and output variables was also low for linear and quadratic relationships.

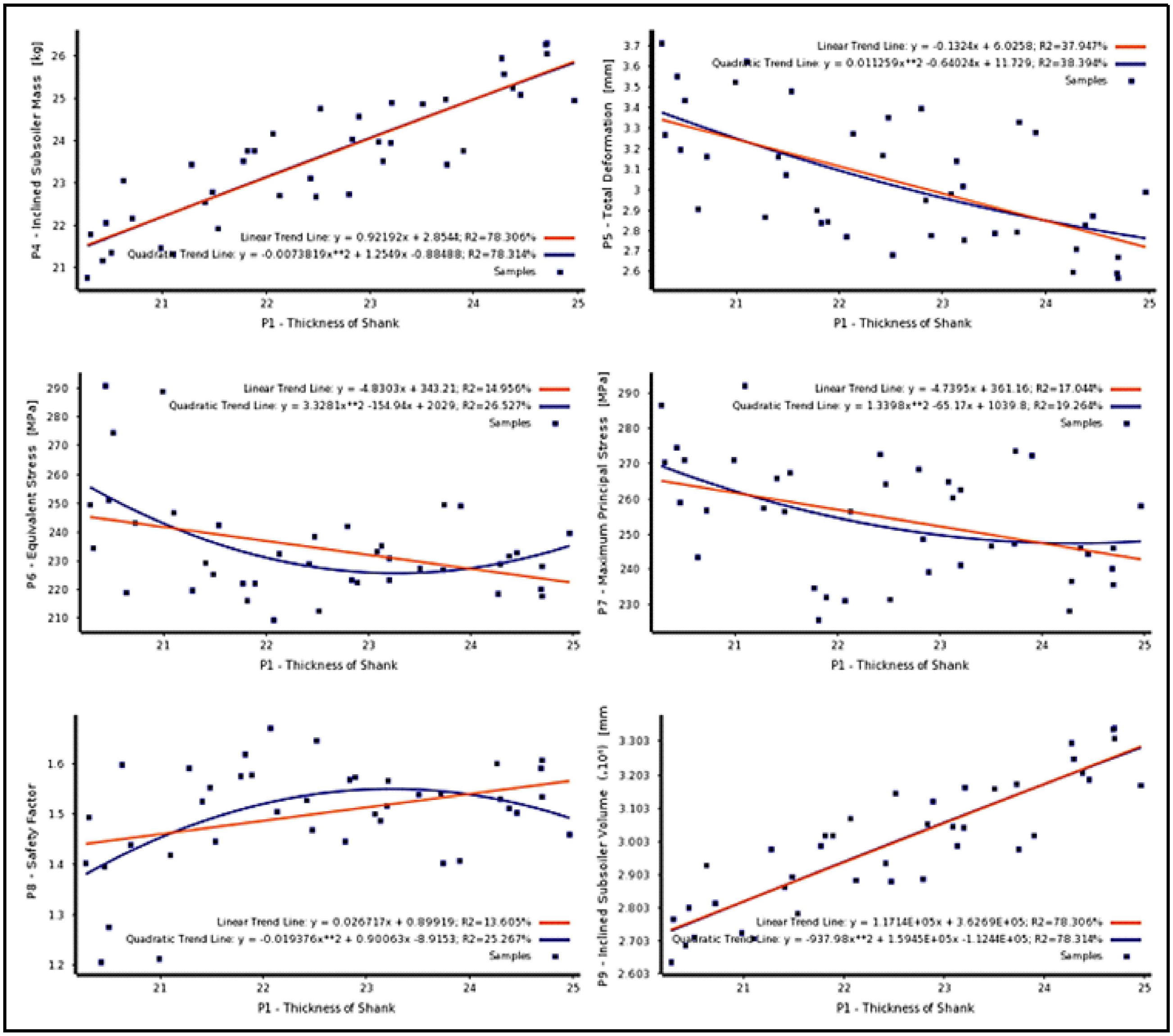

Fig 6. Linear and quadratic relationships between P1 and the output variables

The relationship of P3 with the output variables is shown in Fig 8. The maximum correlation was found between P3 and P5 and the linear and quadratic equations for the relationship are:

Linear $y = -0.0423x + 6.8523$; $R^2 = 62.407\%$

Quadratic $y = 0.0015044Ex2 - 0.3126x + 18.94$; $R^2 = 64.572\%$

where y= P5 (total deformation in mm), x= P3 (width of shank in mm)

P4, P8 and P9 showed increasing trends both linearly and quadratically. On the other hand, P5, P6 and P7 displayed decreasing trends. It was also observed that the quadratic equations showed better relationships compared to the linear equations with better R^2 values for all the output parameters.

Comparison

A comparison between the effects of the different input parameters on the output parameters was made for determining their overall effects. Comparisons were made by fitting regression curves and obtaining the R^2 values. Fig 9 shows the variation of R^2 with the various combinations viz I, II, III and IV.

R^2 for combination II was almost the same as combination I confirming that excluding parameter P3 had negligible effects on the output parameters. R^2 values of combination III and IV were low compared

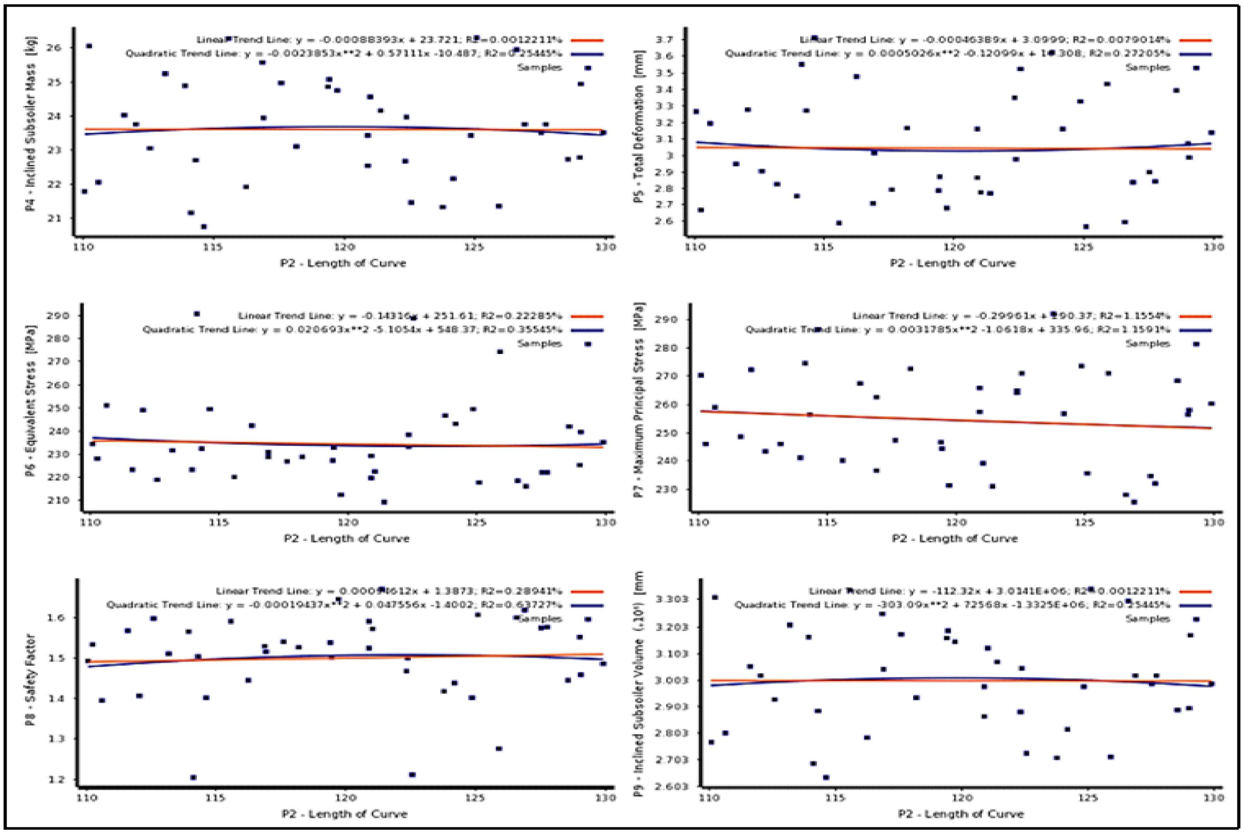

Fig 7. Linear and quadratic relationships between P2 and the output variables

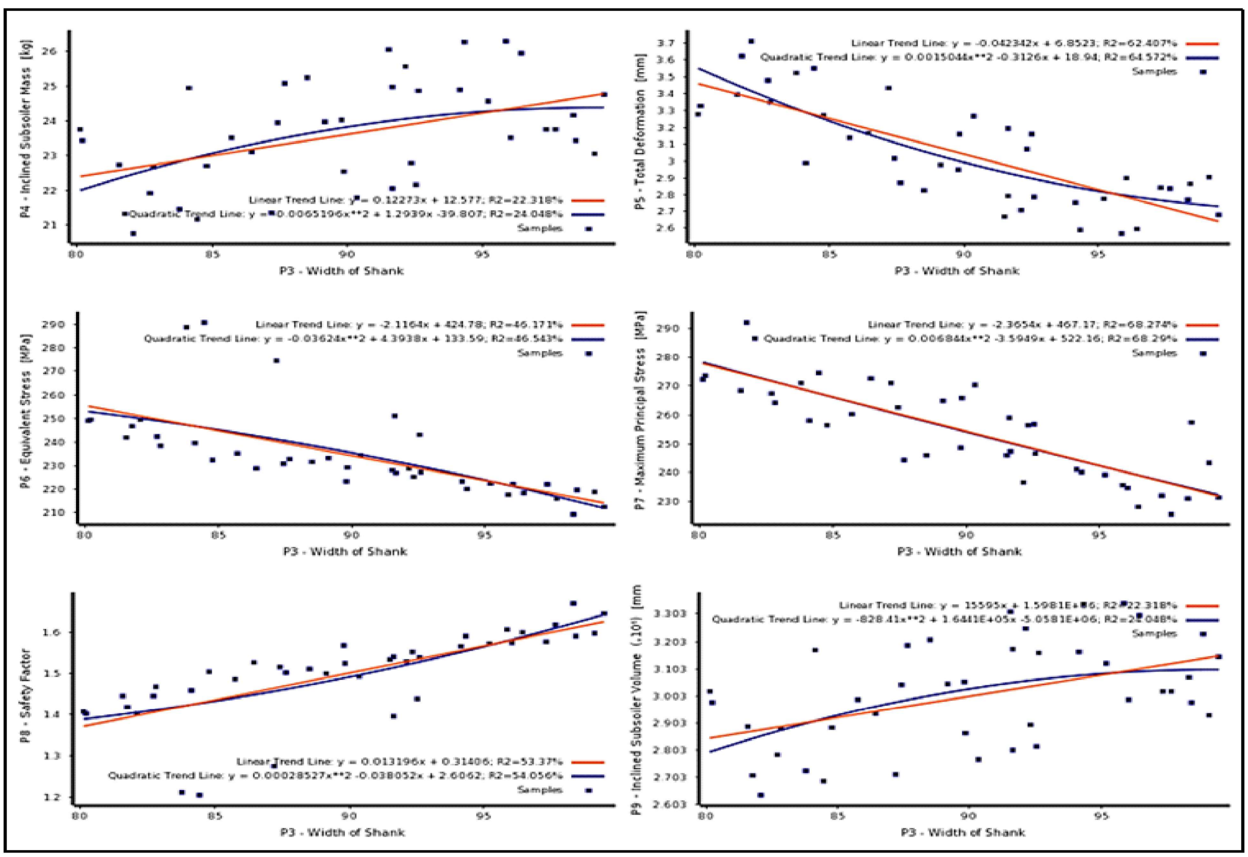

Fig 8. Linear and quadratic relationships between P3 and the output variables

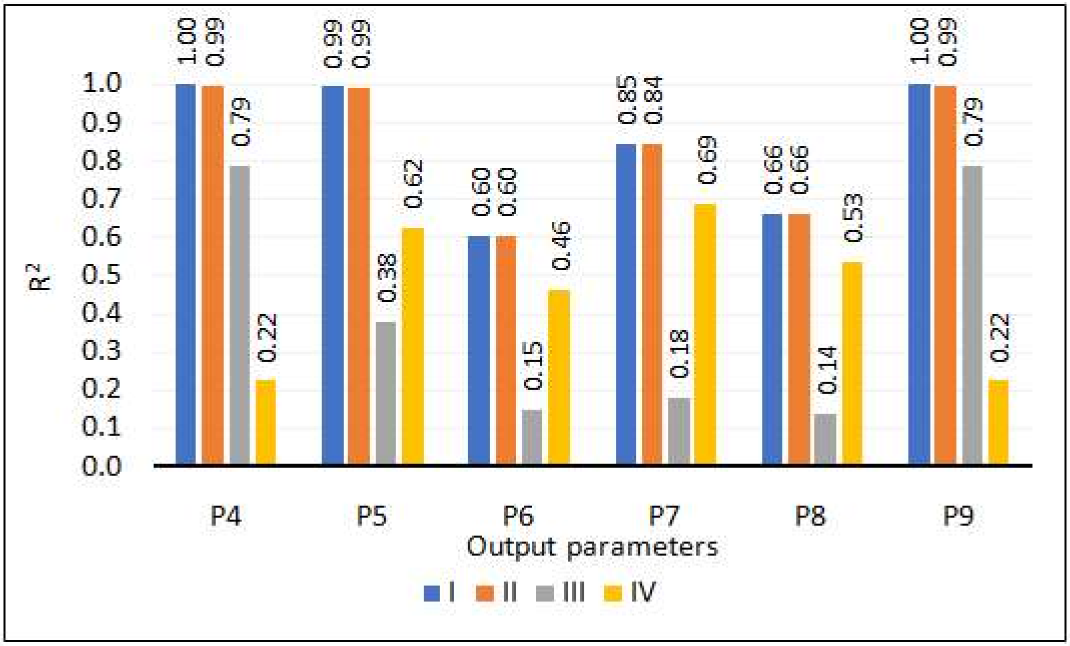

Fig 9. Comparison of R^2 between different combinations of input parameters

to combination I thus confirming that P1 and P3 had a significant impact on all outputs.

CONCLUSION

In this study, the parametric correlation study was conducted to determine the effects of the input parameters viz thickness of shank (P1), length of curve (P2) and width of shank (P3) on the output parameters viz inclined subsoiler mass (P4), total deformation (P5), equivalent stress (P6), maximum principal stress (P7), safety factor (P8) and inclined subsoiler volume (P9). The results of the correlation analysis showed that P1 and P3 affected the output parameters significantly while the effect of P2 on the output parameters was very low. Linear and quadratic relationships between the input and output parameters showed that the quadratic relationships were better at determining between the different variables than the linear ones. P4, P8 and P9 showed increasing trends with an increase in the input parameters while P5, P6 and P7 showed decreasing trends. No trends were observed in the output parameters on varying the input parameter P2. Thus it can be conclude that a parameter correlation study is needed to determine the significance levels of the geometrical parameters knowing how significant the parameters can better evaluate the finite element analysis results.

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