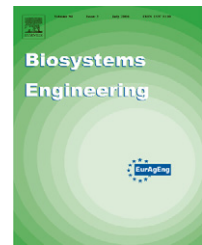


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## Research Paper: PM—Power and Machinery

# Design of the Ethiopian *ard* plough using structural analysis validated with finite element analysis

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The Ethiopian *ard* plough 'Maresha' is a tillage tool that most farmers still use for land preparation. The production of the wooden structure is based on experience, culture, and trial and error methods. In this paper, the basic design of the *ard* plough is presented. The mathematical descriptions (traditional force analysis) are based on static analysis at equilibrium of the structure. The forces considered were the pulling forces provided by a pair of draught animals, the operator input force, gravitational weight of the implement, the normal and tangential interfacial forces acting on the ploughshare and wooden side-wings and the inertial force. The draught, vertical, tangential interfacial and normal interfacial forces of the implement were determined. Moreover, sensitivity of draught and vertical forces to different pulling angles and sensitivity of normal and tangential interfacial forces to different rake angles were investigated. The force analysis was validated by means of the finite element (FE) analysis using the ABAQUS package. It was confirmed that draught force on the ploughshare increased with pulling angle. Similarly, the tangential interfacial force of the implement was higher than the normal interfacial capacity at lower pulling angles. The output of the FEM and traditional calculation resulted in small errors of less than 3% for draught and 5% for vertical forces for small pulling angles  $\leq 30^\circ$ . This study integrates the previous research experiences with theory and computer-based analysis and simulations. The design guidelines and considerations for improving or developing small-scale tillage implements are presented.

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## 1. Introduction

The history of animal traction in eastern and southern Africa, with the exception of Ethiopia and South Africa, started with

the introduction of the ox-plough by the missionaries and white settlers in the early 1920s (Starkey, 1995). While in Ethiopia, animal power has been used for thousands of years, in South Africa it dates back to the 1600s (Starkey, 1995).

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Nomenclature			
$a_1$	height of the tip of handle (where the operator apply force) from horizontal, m	$p$	distance between the position of metal loops with leather strap attachment on the ploughshare and the assumed point where soil resistance is to be concentrated on the ploughshare, m
$a_2$	height of the yoke from horizontal, m	$r$	distance between the position of pin connection of the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing surface, m
$b_1$	horizontal projected distance between the tip of the handle 'M' and the centroid of the ploughshare 'O', m	$\vec{r}_{JO}$	position vector from point 'J' (point of operator's force application) to the ploughshare centroid 'O', m
$b_2$	horizontal projected distance between the middle of the yoke 'B' and the centroid of the ploughshare 'O', m	$\vec{r}_{BO}$	position vector from point 'B' (tip of the beam) to the ploughshare centroid 'O', m
$c_1$	horizontal distance between the centre of the yoke and the position of the right draught animal, m	$\vec{r}_{PW}$	position vector from point 'P' (point of application of pulling force on the side-wing) to the centroid of the left side-wing 'W', m
$c_2$	horizontal distance between the centre of the yoke and the position of the left draught animal, m	$\vec{r}_{QO}$	position vector from point 'Q' (junction point of the beam and the handle assembly) to the ploughshare centroid 'O', m
$d$	depth where forces assumed to be concentrated on the ploughshare, m	$\vec{r}_{TO}$	position vector from point 'T' (point of application of tension by the leather strap/rope on the ploughshare) to the ploughshare centroid 'O', m
$e$	depth where forces assumed to be concentrated on side-wings, m	$\vec{r}_{T'W}$	position vector from point 'T' (point of application of tension by the leather strap/rope on the side-wing) to the centroid of left side wing 'W', m
$F_b$	pulling force acting on the beam top position, N	$\vec{r}_{UO}$	position vector from point 'U' (point of force application by the left draught animal) to the ploughshare centroid 'O', m
$F_n$	pulling force acting at the junction of the beam and the handle, N	$\vec{r}_{VO}$	position vector from point 'V' (point of force application by the right draught animal) to the ploughshare centroid 'O', m
$F_O$	applied force by the operator, N	$\vec{r}_{WO}$	position vector from point 'W' (centroid of the right side-wing where interfacial forces are assumed to be concentrated) to the ploughshare centroid 'O', m
$F_p$	pulling force transferred from the wooden pin to the side-wing, N	$\vec{r}'_{WO}$	position vector from point 'W' (centroid of the left side-wing where interfacial are forces assumed to be concentrated) to the ploughshare centroid 'O', m
$F_x$	draught force, N	$S$	distance between the position of leather strap attachment (including metal loops) on the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing (W for the left side-wing, and W' for the right side-wing), m
$F_{t1}$	pulling force by the right draught animal, N	$T$	tension on the leather strap or rope, N
$F_{t2}$	pulling force by the left draught animal, N	$V$	gravitational force of the implement (excluding weight of the yoke and about 1/3 of the beam), N
$F_z$	vertical force, N	$\alpha_1, \alpha_2$	pulling angle by the right and left draught animals, respectively, degree
$F_1$	tangential interfacial force of the ploughshare, N	$\beta_1, \beta_2$	angle of the beam at the lower and upper position from the ground level, respectively, degree
$F_2$	tangential interfacial force of each side-wing, N	$\gamma$	angle of the side-wing from horizontal, degree
$g$	horizontal projected distance between the centroid of the ploughshare and the side-wing, m	$\theta_1$	share-rake angle (angle of attack), degree
$H$	normal interfacial force of the ploughshare, N	$\theta_2$	inclination angle of the handle, degree
$h$	horizontal projected distance between the junction point of the handle and the beam, and the ploughshare centroid, m	$\lambda$	angle of the applied force by the operator $F_o$ from horizontal, degree
$i$	horizontal unit vector	$\sigma$	tail angle, angle between the side-wing plane surface and the handle, degree
$K$	normal interfacial force of the each side-wing, N		
$k$	vertical unit vector		
$l$	the height of junction point 'Q' of the beam and the handle assembly from the ground level, m		
$M$	total moment, N m		
$M_1$	moment effect of force applied by the operator and transferred to the upper tip of the ploughshare, N m		
$M_W$	moment about centroid of the left side-wing, N m		
$M_O$	moment acting on the centroid of the ploughshare, N m		
$m$	offset dimension of the centroid of the side-wing (where interfacial forces are assumed to be concentrated) from the axis of the handle and the ploughshare, m		
$n$	distance between the point of intersection (of the beam and the handle) and the position of metal loops with leather strap attachment on the ploughshare, m		

$\phi$	angle between the handle (along with its plough-share) and the leather strap, degree	$\Psi$	angle between side-wings, degree
$\varphi$	angle between the side-wing plane surface and the leather strip, degree	$\omega$	angle of force $F_P$ acting on the wooden pin from horizontal, degree

Around 75% of farmers in North and East Africa, South-East Europe, the Near and Far East and Latin America are still using *ard* ploughs of various types (Schmitz, 1991). Depending on a specific design, the ploughs are used for making a furrow and leaving a ridge on one or both sides by partially turning the soil and loosening the layer interface. Tractor-powered tillage implements are used to a limited extent mainly on larger private or commercial farms, but also sometimes for initial tillage of smallholder plots through rental agreements (Pingali et al., 1987; World Bank, 1987). However, the relative simplicity and regenerative character of animal traction technologies, their strong indigenous nature and simple support systems have resulted in their integration into many small-farm systems. Thus, draught animals remain a major power source utilised by a significant number of smallholder farming.

The *ard* type of plough was first described in the poems of Hesiod, in approximately 700 BC (Frazer, 1984). It is the most commonly used implement by Ethiopian highland farmers. It is known locally as 'Maresha' in Amharic, as 'Gindii' in Afaan Oromo, and as 'Mahresha' in Tigrigna. It is a light implement ranging from 17 to 26 kg (Goe, 1987), which makes it possible to be transported to and from the field over different terrains by one person. However, most of the time, 10-year boys can carry and transport both the *ard* and yoke to the fields. The *ard* plough is suitable for use in both sandy soils and heavy crusty clays.

The improvement of the design and performance of the *ard* plough has been undertaken by various researchers and research centres. In 1960, the 'Jimma' plough provided better tillage than the traditional *ard* plough on sandier soils during on-farm trials (UNDP, 2000). In 1968, the Chilallo Agricultural Development Unit (CADU), later changed to the Arsi Rural Development Unit (ARDU), initiated a research programme to develop tillage implements (CADU, 1969, 1970, 1971). In 1970, the 'Vita' plough was introduced, and constructed from a metal mouldboard assembly instead of the metal tine and wings that had characterised previous designs (UNDP, 2000). In order to allow the adaptation of the angle of the handle for easier use, the 'Vita' plough design was modified to come up with the 'Ardu' plough (ARDU & MAS, 1980). In 1976, the Institute of Agricultural Research (IAR) of Ethiopia started developing and testing farm tools and equipment (mouldboard plough, spike tooth harrow, imported tool-bar and hand-operated planter) appropriate for the agricultural conditions in Ethiopia (Berhane, 1979). The International Livestock Centre for Africa (ILCA) conducted research on tillage implements including power requirements, cultivation and weeding times, and crop yields on different soil types (Astatke & Mathews, 1982, 1984). The traditional implement was also modified in view of the selective use of single oxen. This involved replacing the traditional long beam with a shorter beam and skid that connected to a swingle tree and traces (Gryseels et al., 1984; Astatke & Mohammed-Saleem, 1992).

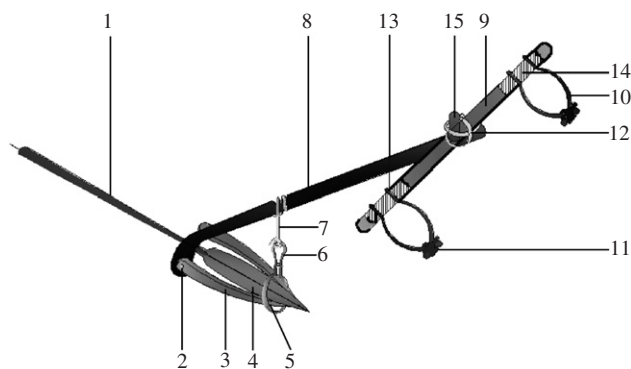
During 1983, the International Livestock Centre for Africa (ILCA) developed a yoke and modified the traditional 'Maresha' enabling the use of a single ox (Astatke & Mohammed-Saleem, 1992). Pathak (1988) accounted for the performance of the components of the type plough and recommended that new ploughs be developed to meet the necessary soil operations with low draught requirements. A reversible animal-drawn plough and ridger have been developed (Gebresenbet, 1995; Gebresenbet et al., 1997; Gebresenbet & Kaoumbtho, 1997) at the Swedish University of Agricultural Sciences, taking into consideration the basic design principle of conventional mouldboard ploughs and the Ethiopian *ard* type of plough. Asefa et al. (1997) developed a four-row seeder in order to solve the problem with the funnel type of hand-metered seed drill. Temesgen (1999) and Temesgen et al. (2001) incorporated the 'Maresha' plough designs into newly developed implements after avoiding the weak points. Accordingly, four implements were developed, namely the modified plough, the ripper/subsoiler, the winged plough, and the tie ridger.

Most developments in the Ethiopian *ard* plough were based on experience, culture, and trial and error methods. However, most of the prototypes were found to be expensive, heavy, complicated and did not fit on the traditional plough frames used in Ethiopia. Therefore, designing an implement must take into account the agricultural and industrial systems, within which the implements are manufactured and operated. Furthermore, efficiency of tillage is measured in terms of draught or input energy (Gill & Vanden Berg, 1968). Optimisation of tillage tool design necessitates minimisation of the input energy and subsequently the draught. The availability of data on the draught requirement of tillage implement is an important factor while selecting tillage implements for a particular farm situation (Sahu & Raheman, 2006). High tillage forces were found to be associated with smaller yield (Neményi et al., 2006). Thus, the optimisation of the Ethiopian *ard* plough is to be directed towards better tillage efficiency.

The objective of the paper is to perform a static analysis on the *ard* plough of Ethiopia, aiming at optimising the structure for minimum draught requirement, structural stability and simplicity and lightweight implement. The results of the force analysis are validated with the finite element (FE) modelling technique.

## 2. Equipment

Most components of the implement (Fig. 1) are products of local timber except for the ploughshare (4) and the metal loops (5) and (6) or the sheath. Blacksmiths make the ploughshare sourcing metal from recycling the broken leaf springs of vehicles, whereas the two metal loops or sheath are made from steel by forging to the required shape and size.



**Fig. 1 – Three-dimensional sketch of the Ethiopian ard plough ‘Maresha’:** (1) handle; (2) wooden pin; (3) side-wing; (4) ploughshare; (5) lower metal loop; (6) upper metal loop; (7) leather stripe (8) beam; (9) yoke; (10) neck holder sticks; (11, 12) leather strap or rope; (13) rubber as washer; (14) leather for safety; (15) centring pin.

The ploughshare (4) is attached to a handle (1) by means of a socket and held in place by friction. The friction in most cases is between the ratchet and the Teflon-like material wound around the bottom end of the handle. The larger diameter of the lower bottom of the beam (8) allows for the hole, through which the handle (1) passes. The lower bottom of the beam also helps as counter weight to keep the ploughshare in the soil. The clearance in this assembly helps to vary the rake angle by inserting any wooden spacer. The side-wings (3) are two pieces of wood with opposite orientation in order to be assembled at both sides of the ploughshare (4). The rear ends are pinned to the beam (8), located behind the joint position of the handle (1) and the beam (8), by means of a pin-like wooden material (2) forming a ‘sledge’ shape. The other ends of these side-wings are held together with the ploughshare (4) by means of a metal loop (5). Another metal loop (6) is interlinked with the first loop, and a piece of wood is inserted between the two metal loops to reduce metal-to-metal friction. In many cases, only one component is used instead of two loops. The metal loop (6) is then fastened to the beam (8) using a strap made from a combination of leather and rubber (7). However, in many cases farmers use a simple rope. The beam (8) is assembled to the yoke (9) by means of a centring pin (15) inserted to the hole at the centre of the yoke and the leather strap or rope (12). The yoke (9) has two holes at each end, into which the four-neck holder ‘sticks’ (10) with different orientations are inserted. These ‘sticks’ are used as a guide to keep the oxen at a relatively balanced position by introducing a constant gap between the two oxen.

### 3. Force analysis

The forces acting on the traditional ard plough of Ethiopia are the pulling force applied by the draught animal, the gravitational force (weight of implement), the force exerted by the operator, the gravitational force of the soil, the soil resistance, the interface forces between the soil and plough (share and side-wings at the front and back sides) and the inertia force.

The mathematical description of the ard plough is discussed based on the static analysis of the structure at equilibrium. The dynamic effect was considered negligible, since ploughing with animal traction occurs at a low speed compared to the ploughing speed with agricultural tractors. To develop mathematical equations, the forces acting on the plough and the dimensional relation of the structure were taken into account.

#### 3.1. Assumptions for the force analysis

The following assumptions were taken into account for further approximation of detailed force analysis.

- (1) The implement is symmetric in shape.
- (2) The ploughshare performs soil penetration. The side-wings are used for crack propagation and furrow making. Thus, the major portion of soil resistance acts on the ploughshare, allowing the tangential  $F_2$  and normal  $K$  interfacial forces of each side-wing acting on the two side-wings to be ignored.
- (3) The lateral force applied by the operator is to reduce draught requirement and also to keep the width of ploughing. The operator usually vibrates the plough in the lateral direction to assist the loosening and breaking process. Though it is a continuous process, its effect can be minimised by introducing a lateral slot at the juncture of the beam and the handle assembly. Thus, its effect can be neglected.
- (4) The effect of inertial force is negligible because of the low speed of tillage process.
- (5) Soil type and soil properties were neglected, since no interaction analysis between the soil and ploughshare was considered.
- (6) The tangential interfacial force at the bottom side of the ploughshare and side-wings has a significant effect during initiation of the soil penetration process, because of initial full-surface contact with soil. Depending on the soil texture, the surface contact decreases and its magnitude reduces as the tillage process progresses. Thus, this force can be neglected during development of the mathematical equations.
- (7) The magnitude of the downward force exerted on the handle by the operator increases to enhance the penetration of high-resistance soils. In other cases, this force is very small.
- (8) The handle and ploughshare axes are collinear, for which share-rake angle  $\theta_1$  and inclination angle of the handle  $\theta_2$  are equal ( $\theta_1 = \theta_2 = \theta$ ).
- (9) The two draught animals have same size and weight, and walk at the same pace. For this assumption, the pulling force by the right draught animal  $F_{t1}$  equals the pulling force by the left draught animal  $F_{t2}$  and pulling angle by right  $\alpha_1$  and left  $\alpha_2$  draught animals are also equal ( $F_{t1} = F_{t2} = F_t$  and  $\alpha_1 = \alpha_2 = \alpha$ ).
- (10) The two draught animals keep their position equidistant from the centring pin, for which the horizontal distance between the centre of the yoke and the position of the right  $c_1$  and left  $c_2$  draught animal are equal ( $c_1 = c_2 = c$ ).

### 3.2. Input forces

The pulling forces applied by the two oxen  $F_{t1}$  and  $F_{t2}$  in N can be written as a function of angles  $\alpha_1$  and  $\alpha_2$  in degree, respectively as follows [see Fig. 2(a)]:

$$\vec{F}_{t1} = \vec{F}_{t1x} + \vec{F}_{t1z} = F_{t1}\vec{i} \cos \alpha_1 + F_{t1}\vec{k} \sin \alpha_1, \quad (1)$$

$$\vec{F}_{t2} = \vec{F}_{t2x} + \vec{F}_{t2z} = F_{t2}\vec{i} \cos \alpha_2 + F_{t2}\vec{k} \sin \alpha_2, \quad (2)$$

where  $\vec{i}$  is a unit vector of horizontal X axis;  $\vec{k}$  is a unit vector of vertical Z axis; and  $\alpha_1, \alpha_2$  are pulling angles by the right and left draught animals, respectively, in degree.

Vertical (Z axis), longitudinal (XZ plane) and lateral (YZ plane) forces applied by the operator, control depth and reduce draught requirement. Vibration of the plough in the lateral direction, perpendicular to the ploughing direction, assists in the loosening and breaking process of the soil. Here, the vertical and longitudinal forces are considered because of the relative importance for depth control that has significant impact on draught requirement and cultivation. The operator input force  $F_O$  in N is written as [Fig. 2(a)]:

$$\vec{F}_O = \vec{F}_{Ox} + \vec{F}_{Oz} = F_O\vec{i} \cos \lambda - F_O\vec{k} \sin \lambda, \quad (3)$$

where  $\lambda$  is the angle in degree of the applied force by the operator  $F_O$  from horizontal.

given as follows [see Figs. 2(b) and (c)]:

$$\vec{K} = \vec{K}_x + \vec{K}_z = -K\vec{i} \sin \gamma - K\vec{k} \cos \gamma. \quad (6)$$

Similarly, the tangential interfacial force of each side-wings  $F_2$  in N is given as follows [see Figs 2(b) and (c)]:

$$\vec{F}_2 = \vec{F}_{2x} + \vec{F}_{2z} = -F_2\vec{i} \cos \gamma + F_2\vec{k} \sin \gamma. \quad (7)$$

The load of gravitational force of the implement (excluding the weight of the yoke and about a third of the beam, which is assumed to be carried by the draught animals) was assumed to be concentrated on the centroid of the ploughshare, and written as

$$\vec{V} = -V\vec{k} \quad (8)$$

where  $V$  is gravitational force in N of the implement (excluding weight of the yoke and a third of the beam)

### 3.4. Force balance

The implement structure is considered as a rigid body, and analysed at static equilibrium. A rigid body is considered to be in equilibrium when both the sums of the resultant forces and the resultant moments are zero ( $\sum \vec{F} = 0; \sum M = 0$ ).

From the free body diagrams shown in Fig. 2, the normal interfacial forces of the ploughshare  $H$  and each side-wing  $K$  are given by Eqs. (9) and (10), respectively.

$$+ \rightarrow \sum \vec{F}_x = 0; \quad + \uparrow \sum \vec{F}_z = 0$$

$$H = \left\{ \frac{F_{t1}(\tan \gamma \sin \alpha_1 - \cos \alpha_1) + F_{t2}(\tan \gamma \sin \alpha_2 - \cos \alpha_2) - F_O(\tan \gamma \sin \lambda + \cos \lambda) + F_1(\tan \gamma \sin \theta_1 + \cos \theta_1) + 2F_2(\tan \gamma \sin \gamma + \cos \gamma) - V \tan \gamma}{(\tan \gamma \cos \theta_1 - \sin \theta_1)} \right\} \quad (9)$$

$$K = \frac{1}{2} \left\{ \frac{F_{t1}(\cos \alpha_1 - \tan \theta_1 \sin \alpha_1) + F_{t2}(\cos \alpha_2 - \tan \theta_1 \sin \alpha_2) + F_O(\tan \theta_1 \sin \lambda + \cos \lambda) - F_1(\cos \theta_1 - \tan \theta_1 \sin \theta_1) - 2F_2(\tan \theta_1 \sin \gamma + \cos \gamma) + V \tan \theta_1}{(\sin \gamma - \tan \theta_1 \cos \gamma)} \right\} \quad (10)$$

### 3.3. Output forces (capacities)

The normal interfacial force of the ploughshare  $H$  in N, i.e. the implement structural force that withstands the normal force of soil resistance, is written as component forces as a function of inclination angle of the ploughshare  $\theta_1$  in degree as follows [see Figs 2(b) and (c)]:

$$\vec{H} = \vec{H}_x + \vec{H}_z = -H\vec{i} \sin \theta_1 - H\vec{k} \cos \theta_1. \quad (4)$$

Similarly, the tangential interfacial force on the ploughshare  $F_1$  in N, shown in Fig. 2 is given as follows:

$$\vec{F}_1 = \vec{F}_{1x} + \vec{F}_{1z} = -F_1\vec{i} \cos \theta_1 + F_1\vec{k} \sin \theta_1. \quad (5)$$

For the normal and tangential forces of the side-wings, it was assumed that same weight of soil with similar soil properties pass over both side-wing surfaces. Moreover, both wings have geometrical similarity with opposite orientation, i.e. symmetrical to the ploughshare axis. The normal interfacial force of the side-wing  $K$  in N is written as component forces as a function of angle  $\gamma$  in degree the inclination of side-wing from horizontal; and is

### 3.5. Moment balance

For moment at point 'O',  $\{(x,y,z) \rightarrow (0,0,0)\}$ , where all forces on the ploughshare were assumed to be concentrated, the coupling effects of  $H, F_1$ , and  $V$  vanish because of zero position vector (see Fig. 3). Since the weight of the yoke and about 1/3 of the beam is supported by the draught animals and directly transferred to the ground, it does not have coupling effect on the structure. Hence, point 'O' is considered as the centroidal point on the ploughshare of soil-metal interface. The centroid can be approximated by area centroid considering the small soil-tool interface area. Accordingly, the coupling effect  $M_O$  on the ploughshare centroid due to the pulling force by the draught animals and the operator input force can be deduced from total moment balance  $M$  in N m, given as follows:

$$\sum M = (\vec{r}_{jO} \times \vec{F}_O) + (\vec{r}_{vO} \times \vec{F}_{t1}) + (\vec{r}_{uO} \times \vec{F}_{t2}) + (\vec{r}_{wO} \times \vec{K}) + (\vec{r}_{wO} \times \vec{F}_2) + (\vec{r}_{w'O} \times \vec{K}) + (\vec{r}_{w'O} \times \vec{F}_2) + M_O = 0, \quad (11)$$



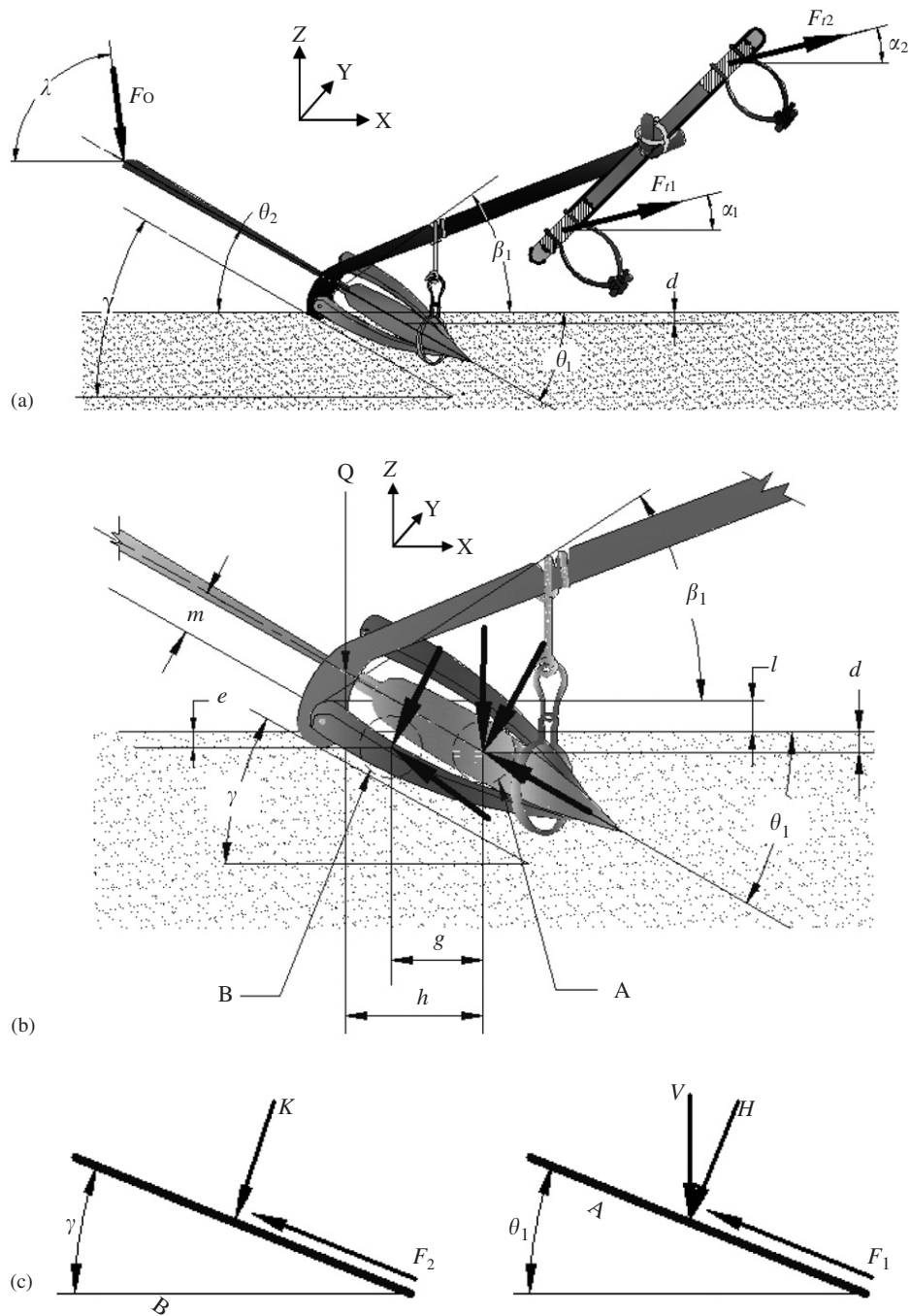
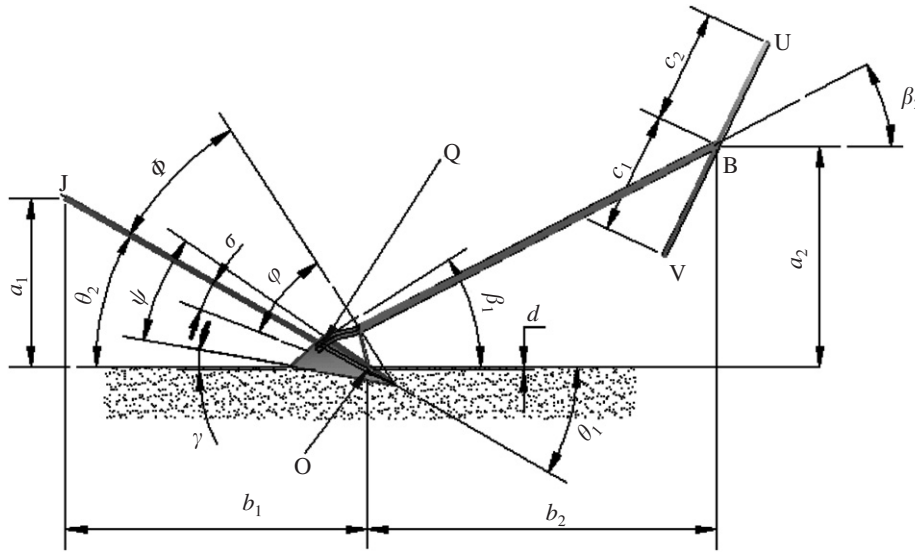


Fig. 2 – Forces acting on the Ethiopian *ard* plough ‘Maresha’: (a) input forces; (b) output forces at the share and two side-wings; (c) detailed force analysis output on ploughshare A and side-wing B:  $d$ , the depth where forces assumed to be concentrated on ploughshare;  $e$ , depth where forces assumed to be concentrated on side-wings;  $F_O$ , operator force;  $F_{t1}$ ,  $F_{t2}$ , pulling forces by the two draught animals;  $F_1$  and  $F_2$ , tangential interfacial force of ploughshare and each side-wing, respectively;  $g$ , horizontal projected distance between centroid of ploughshare and side-wing;  $H$ , normal interfacial force of ploughshare;  $h$ , horizontal projected distance between the junction point of the handle and the beam, and the ploughshare centroid;  $l$ , the height of junction point  $Q$  of the beam and the handle assembly from the ground level;  $m$ , offset dimension of centroid of side-wing (where interfacial forces are assumed to be concentrated) from the axis of the handle and the ploughshare;  $V$ , gravitational force of the implement (excluding weight of yoke and about 1/3 of the beam);  $\alpha_1$  and  $\alpha_2$ , pulling angle by the draught animal 1 (right) and the draught animal 2 (left);  $\beta_1$  and  $\beta_2$ , angle of beam, at lower position from ground level;  $\gamma$ , angle of side-wing from horizontal;  $\theta_1$ , share-rake angle (angle of attack);  $\theta_2$ , inclination angle of the handle;  $\lambda$ , angle of the applied force by the operator  $F_O$  from horizontal.



**Fig. 3 – Line representation and respective dimensions of Ethiopian ard plough ‘Maresha’:**  $a_1$ , height of the tip of handle (where the operator apply force) from horizontal;  $a_2$ , height of the yoke from horizontal;  $b_1$ , horizontal projected distance between the tip of handle J and the centroid of ploughshare O;  $b_2$ , horizontal projected distance between middle of the yoke B and the centroid of ploughshare O;  $c_1$ , the horizontal distance between the centre of the yoke and the position of the right draught animal;  $c_2$ , the horizontal distance between the centre of the yoke and the position of the left draught animal;  $d$ , the depth where forces assumed to be concentrated on ploughshare;  $e$ , depth where forces assumed to be concentrated on side-wings;  $F_O$ , operator force; Q, junction point of the beam and the handle assembly;  $\beta_1$  and  $\beta_2$ , angle of the beam, at lower position from ground level;  $\gamma$ , angle of side-wing from horizontal;  $\theta_1$ , rake angle (angle of attack);  $\theta_2$ , inclination angle of the handle;  $\lambda$ , angle of the applied force by the operator  $F_O$  from horizontal;  $\sigma$ , tail angle, angle between the side-wing plane surface and the handle;  $\phi$ , angle between handle (along with its ploughshare) and the leather strap;  $\varphi$ , angle between side-wing plane surface and the leather strip and  $\psi$ , angle between the side-wings.

where  $M_O$  is moment acting on centroid of the ploughshare in Nm;  $\vec{r}_{JO}$  is position vector from point ‘J’, point of operator’s force application, to the ploughshare centroid ‘O’ in m;  $\vec{r}_{UO}$  is position vector from point ‘U’, point of force application by the left draught animal, to the ploughshare centroid ‘O’ in m;  $\vec{r}_{VO}$  is position vector from point ‘V’, point of force application by the right draught animal, to the ploughshare centroid ‘O’ in m;  $\vec{r}_{WO}$  is position vector from point ‘W’, centroid of the left side-wing where interfacial forces assumed to be concentrated, to the ploughshare centroid ‘O’ in m;  $\vec{r}_{W'O}$  is position vector from point ‘W’’, centroid of the right side-wing where interfacial forces assumed to be concentrated, to the ploughshare centroid ‘O’ in m.

$$M_O = \{-F_{t1}[b_2 \sin \alpha_1 - (a_2 + d) \cos \alpha_1] - F_{t2}[b_2 \sin \alpha_2 - (a_2 + d) \cos \alpha_2] + F_O[(a_1 + d) \cos \lambda - b_1 \sin \lambda] - 2K[g \cos \gamma + (d - e) \sin \gamma] + 2F_2[g \sin \gamma - (d - e) \cos \gamma]\}, \quad (12)$$

where  $a_1$  is height of the tip of handle, where the operator apply force ‘J’, from horizontal in m;  $a_2$  is height of the yoke from horizontal in m;  $b_1$  is horizontal projected distance between the tip of handle ‘J’ and centroid of ploughshare ‘O’ in m;  $b_2$  is horizontal projected distance between middle of yoke ‘B’ and centroid of the ploughshare ‘O’ in m;  $d$  is the depth where forces assumed to be concentrated on the

ploughshare ‘O’ in m;  $e$  is the depth where forces assumed to be concentrated on side-wings in m;  $g$  is horizontal projected distance between centroid of the ploughshare ‘O’ and of the side-wing in m.

3.5.1. Pulling force between the yoke and the beam

The pulling force  $F_b$  on the beam in N can be derived directly from the yoke input forces from force balance. At equilibrium, the sum of forces between the yoke and the beam in X and Z directions equals zero (Figs. 2 and 4). The transferred pulling force from the two draught animals to the beam  $F_b$  and its angle of action  $\beta_2$  can be given by Eqs. (13) and (14), respectively, as follow:

$$F_b = \frac{F_{t1} \cos \alpha_1 + F_{t2} \cos \alpha_2}{\cos \beta_2} = \frac{F_{t1} \sin \alpha_1 + F_{t2} \sin \alpha_2}{\sin \beta_2}, \quad (13)$$

$$\beta_2 = \tan^{-1} \left\{ \frac{F_{t1} \sin \alpha_1 + F_{t2} \sin \alpha_2}{F_{t1} \cos \alpha_1 + F_{t2} \cos \alpha_2} \right\}, \quad (14)$$

where  $\beta_2$  is angle of the beam at the upper position from ground level in degree.

3.5.2. Pulling force between the beam and other components excluding the yoke

From Figs. 2 and 4, at equilibrium condition, the normal forces acting on the ploughshare H in N and of each side-wing K in N are expressed by two equations similar to the

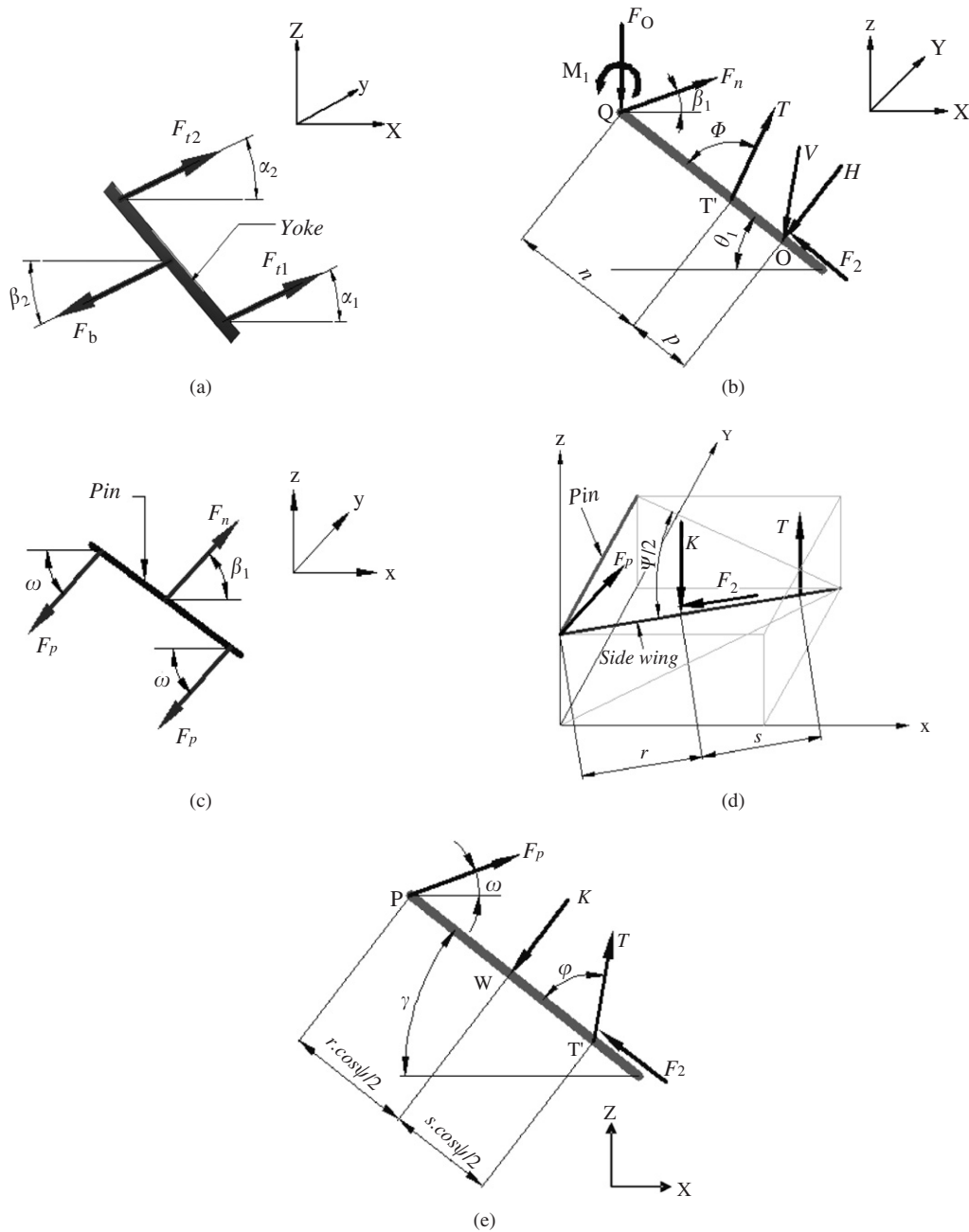


Fig. 4 – Pulling force acting on different parts of the Ethiopian *ard* plough ‘maresha’: (a) force transfer between the yoke and the beam; (b) forces acting on ploughshare; (c) force acting on wooden pin; (d) force acting on side-wing in two-dimensional view (X-Z plane); (e) force acting on side-wing in three-dimensional view  $F_b$ , pulling force acting on the beam, top position, N;  $F_n$ , pulling force acting at the junction of the beam and the handle;  $F_o$ , operator force;  $F_p$ , pulling force transferred from the wooden pin to the side-wing;  $F_1$  and  $F_2$ , tangential interfacial force of ploughshare and each side-wing, respectively; H, normal interfacial force of ploughshare; K, normal interfacial force of each side-wing;  $M_1$ , moment effect of force applied by the operator and transferred to the upper tip of ploughshare; n, the distance between the point of intersection (of the beam and the handle) and the position of metal loops with leather strap attachment on the ploughshare; p, the distance between the position of metal loops with leather strap attachment on ploughshare and the assumed point where soil resistance is to be concentrated on the ploughshare; Q, junction point of the beam and the handle assembly; r, the distance between the position of pin connection of the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing surface; s, the distance between the position of leather strap attachment (including metal loops) on the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing (W for left-side wing, and W' for right side-wing); T, tension on leather strap or rope; V, gravitational force of the implement (excluding weight of yoke and about 1/3 of the beam);  $\alpha_1$  and  $\alpha_2$ , pulling angle by draught animal 1 (right) and draught animal 2 (left);  $\beta_1$  and  $\beta_2$ , angle of the beam, at lower position from ground level;  $\gamma$ , angle of side-wing from horizontal;  $\theta_1$ , rake angle (angle of attack);  $\phi$ , angle between the handle (along with its ploughshare) and the leather strap;  $\varphi$ , angle between side wing plane surface and the leather strip;  $\Psi$ , angle between the side-wings;  $\omega$ , angle of  $F_p$  acting on the wooden pin from horizontal.



Eqs. (9) and (10), respectively. However, the pulling force by the two draught oxen  $F_{t1}$  and  $F_{t2}$  is replaced by pulling force acting on beam, top position  $F_b$ . The angle of action  $\beta_2$  becomes:

$$\beta_2 = \tan^{-1} \left\{ \frac{H \cos \theta_1 + F_O \sin \lambda - F_1 \sin \theta_1 - 2F_2 \sin \gamma + 2K \cos \gamma + V}{H \sin \theta_1 - F_O \cos \lambda + F_1 \cos \theta_1 + 2F_2 \cos \gamma + 2K \sin \gamma} \right\}. \quad (15)$$

#### Moment balance

Moment equals zero at the point 'O' where the forces on the ploughshare are assumed to be concentrated, and thus the coupling effect of  $H$  and  $F_1$  vanishes. Accordingly, the coupling effect  $M_O$  [Eq. (16)] on the ploughshare resulting from the pulling force  $F_b$ , the operator input force, and the normal and tangential interfacial forces of both side-wings can be deduced as follows:

$$\begin{aligned} \sum M = & (\vec{r}_{BO} \times \vec{F}_b) + (\vec{r}_{JO} \times \vec{F}_O) + (\vec{r}_{WO} \times \vec{K}) \\ & + (\vec{r}_{WO} \times \vec{F}_2) + (\vec{r}_{WO} \times \vec{K}) \\ & + (\vec{r}_{WO} \times \vec{F}_2) + M_O = 0, \end{aligned} \quad (16)$$

$$\begin{aligned} M_O = & \{ F_b [b_2 \sin \beta_2 - (a_2 + d) \cos \beta_2] \\ & + F_O [b_1 \sin \lambda + (a_1 + d) \cos \lambda] \\ & - 2K [g \cos \gamma + (d - e) \sin \gamma] \} \\ & + 2F_2 [g \sin \gamma - (d - e) \cos \gamma], \end{aligned} \quad (17)$$

where  $\vec{r}_{BO}$  is position vector from point 'B' at the top tip of the beam to the ploughshare centroid 'O' in m.

Due to the basic design of the plough, the part of the beam the share is curved upwards. This makes the line of pull coincide with the line of the resultant pulling force, which reduces draught requirement.

### 3.5.3. Pulling force on the ploughshare

#### Force balance

From Fig. 4, the tension  $T$  on the leather strap at equilibrium, considering maximum operator input force acting vertical, can be given as follows:

$$T = \frac{H(\cos \theta_1 - \tan \beta_1 \sin \theta_1) - F_1(\sin \theta_1 + \tan \beta_1 \cos \theta_1) + V + F_O}{[\sin(180 - \theta_1 - \varphi) - \tan \beta_1 \cos(180 - \theta_1 - \varphi)]}, \quad (18)$$

where  $T$  is tension on leather strap or rope in N;  $\beta_1$  is angle of beam at lower position from ground level in degree;  $\varphi$  is angle between side-wing plane surface and the leather strip in degree.

#### Moment balance

The moment balance at point 'O' (Fig. 4), considering  $(x, y, z)$  at this point to be  $(0, 0, 0)$  is given by

$$\sum M_O = (\vec{r}_{QO} \times \vec{F}_n) + (\vec{r}_{TO} \times \vec{T}) + M_1 = 0, \quad (19)$$

where  $F_n$  is pulling force acting at the junction of the beam and the handle in N;  $M_1$  is moment effect of force applied by the operator and transferred to the upper tip of the ploughshare in Nm;  $\vec{r}_{TO}$  is position vector from point 'T', point of application of tension by the leather strap/rope on the ploughshare, to the ploughshare centroid 'O' in m;  $\vec{r}_{QO}$  is position vector from point 'Q' (junction point of the beam and the handle assembly) to the ploughshare centroid 'O' in m.

After matrix formulation, the tension on the leather strap is given as follows:

$$T = \frac{1}{p} \left\{ \frac{F_n(n+p)[\cos \theta_1 \sin \beta_1 + \sin \theta_1 \cos \beta_1] - M_1}{[(\cos \theta_1 \sin(180 - \theta_1 - \varphi) + \sin \theta_1 \cos(180 - \theta_1 - \varphi))]} \right\}, \quad (20)$$

where  $n$  is the distance between the point of intersection (of the beam and the handle) and the position of metal loops with leather strap attachment on the ploughshare in m;  $p$  is the distance between the position of metal loops with leather strap attachment on the ploughshare and the assumed point where soil resistance is to be concentrated on the ploughshare in m.

### 3.5.4. Pulling force at wooden pin

Based on the assumption that the side-wings are symmetrical in shape and face moving soil of the same weight, physical and mechanical properties, the draught force transferred from the beam to both wings has the same magnitude. Neglecting the effect of offset dimension between the force acting on pin and at the junction point of the beam and the handle, at equilibrium condition, the angle of pulling  $\omega$  and the pulling force on the pin  $F_p$  (Fig. 4) is given as follows:

$$\omega = \beta_1 \text{ and } F_p = \frac{1}{2}F_n, \quad (21)$$

where  $\omega$  is angle of force  $F_p$  acting on the wooden pin from horizontal in degree;  $F_p$  is pulling force transferred from the wooden pin to the side-wing in N.

### 3.5.5. Pulling force at side wings

#### Force balance

From the force balance, the angle of pulling (Fig. 4) on the side-wing  $\omega$  is given by Eq. (22). This angle is equal and opposite of the angle of pulling on the pin.

$$\omega = \tan^{-1} \left\{ \frac{K \cos \gamma - F_2 \sin \gamma - T \sin(180 - \gamma - \varphi)}{K \sin \gamma + F_2 \cos \gamma - T \cos(180 - \gamma - \varphi)} \right\}. \quad (22)$$

#### Moment equation

Taking the moment at point 'W' [Fig. 4(d)], and considering  $(x, y, z)$  at this point to be  $(0, 0, 0)$ , the pulling force  $F_p$  acting on the each side wing is given by Eq. (24)

$$\sum M_W = (\vec{r}_{PW} \times \vec{F}_p) + (\vec{r}_{TW} \times \vec{T}). \quad (23)$$

where  $M_W$  is moment about centroid of the left side-wing in Nm;  $\vec{r}_{PW}$  position vector from point 'P' (point of application of pulling force on the side-wing) to the centroid of the left side-wing 'W' in m;  $\vec{r}_{TW}$  is position vector from point 'T' (point of application of tension by the leather strap on the side-wing) to the centroid of left side-wing 'W' in m.

$$F_p = \frac{sT}{r} \left\{ \frac{\cos \gamma \cos \frac{\psi}{2} \sin(180 - \gamma - \varphi) + \sin \gamma \cos(180 - \gamma - \varphi)}{\cos \gamma \cos \frac{\psi}{2} \sin \omega + \sin \gamma \cos \omega} \right\}, \quad (24)$$

where  $r$  is the distance between the position of pin connection of the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing surface in m;  $s$  is distance between the position of leather strap attachment (including metal loops) on the side-wing and the point where soil resistance is assumed to be concentrated on the side-wing in m;  $\psi$  is angle between two side-wings in degree.

Considering the assumptions mentioned in 3.1, Eq. (9) can be re-written as follows:

$$H = \left\{ \frac{2F_t \cos \alpha + F_O \cos \lambda - F_1 \cos \theta}{\sin \theta} \right\} = \left\{ \frac{2F_t \sin \alpha - F_O \sin \lambda + F_1 \sin \theta - V}{\cos \theta} \right\}. \quad (25)$$

Accordingly, from Eqs. (1)–(5) and (8), the normal and tangential interfacial forces of the structure at the ploughshare can be written in terms of animals pulling force, operator input force, and implement weight by the following two equations, respectively:

$$F_1 = \frac{2F_t(\cos \alpha - \tan \theta \sin \alpha) + F_O(\cos \lambda + \tan \theta \sin \lambda) + V \tan \theta}{(\tan \theta \sin \theta + \cos \theta)}, \quad (26)$$

$$H = \frac{2F_t(\tan \theta \cos \alpha + \sin \alpha) + F_O(\tan \theta \cos \lambda - \sin \lambda) - V}{(\cos \theta + \tan \theta \sin \theta)}. \quad (27)$$

From Eqs. (26) and (27) the draught and vertical forces can be calculated. For instance, for the case, when the effects of gravitational weight of the implement and the operator's input force were not considered, these formulae are written as:

$$F_x = F_1 \cos \theta + H \sin \theta, \quad (28)$$

$$F_z = H \cos \theta - F_1 \sin \theta, \quad (29)$$

where  $F_x$  is draught force in N;  $F_z$  is vertical force in N.

Similarly, the force acting on the beam  $F_b$  and its angle of action  $\beta_2$  are given by the following two equations, respectively:

$$F_b = 2F_t = \frac{H \sin \theta - F_O \cos \lambda + F_1 \cos \theta}{\cos \beta_2} = \frac{H \cos \theta + F_O \sin \lambda - F_1 \sin \theta + V}{\sin \beta_2}, \quad (30)$$

$$\beta_2 = \tan^{-1} \frac{H \cos \theta + F_O \sin \lambda - F_1 \sin \theta + V}{H \sin \theta - F_O \cos \lambda + F_1 \cos \theta}. \quad (31)$$

From Eqs. (13) and (14)

$$\beta_2 = \alpha \text{ and } F_b = 2F_t. \quad (32)$$

The force  $F_b$  can be measured or derived directly from interfacial force, implement weight and operator input force.

Considering the above approach, for stable operation, the sum of vertical downward forces has to be greater or equal to the sum of vertical upward forces, i.e.  $V + 2K_z + H_z + F_O \geq 2F_{tz} + 2F_{lz} + 2F_{zz}$ . For high-resistive soils, the operator should apply a force  $F_O$  on the handle to assist the plough to penetrate soil during tillage process. The alignment of the line of pull with the line of pulling of the resultant force acting on the plough body could benefit in minimising impact of bending moment. Such an arrangement decreases the bending moment on the beam so that the beam is subjected mainly to tension and hence a lighter beam can be used.

## 4. Results

### 4.1. Sensitivity of draught and vertical capacities of the implement with pulling angle

The sensitivity analysis is required to investigate and visualise the effect of the dimensional parameters and forces acting on the structure of the *ard* plough. Here, the word 'force' is substituted by 'capacity' to indicate structure output forces that can be provided at the ploughshare. The sensitivity analysis was conducted for the draught  $F_x$ , vertical  $F_z$ , normal interfacial  $F_1$  and tangential  $H$  capacities provided on the ploughshare. This analysis was based on calculations made using Eqs. (26)–(29) and the following assumed parameters:

- (1) rake angle  $\theta = 19^\circ$ ;
- (2) animal pulling force  $F_t = 600$  N at  $\beta_2 = \alpha = 10^\circ$ – $60^\circ$ ;
- (3) implement gravitational weight  $V = 150$  N; and
- (4) operator force  $F_O = 150$  N at  $\lambda = 60^\circ$ .

From the sensitivity analysis outputs given in Table 1, it can be concluded that the weight of the implement affected the vertical capacity, but not the horizontal capacity. The operator's input force affected both the vertical and horizontal capacities. However, both the weight of the implement and operator's input force affected the tangential and normal interfacial capacities. The tangential interfacial capacity of the implement was higher than the normal interfacial capacity at lower pulling angles. The horizontal capacity decreased (draught requirement increased) with the pulling angle, whereas the downwards vertical capacity increased (downwards vertical force requirement decreased), which will introduce the problem of keeping the ploughshare in the soil. This increases the draught requirement and decreases the downwards force of tillage process. Draught requirement is smaller at smaller pulling angle  $\beta$ . In fact, this angle is used in practice for depth regulation. For primary tillage, it is set small to reduce depth so that the animal can pull the plough. For secondary tillage, this angle is usually increased to increase depth of tillage. The operator input force decreased the upward vertical force to keep the ploughshare at the proper tillage depth. In general, the analysis indicates that the maximum draught capacity can be provided at small pulling angles. This conclusion is inline with what was reported by Gebresenbet *et al.* (1997) that the angle of pull for the Ethiopian traditional plough varies from  $10^\circ$  to  $20^\circ$ .

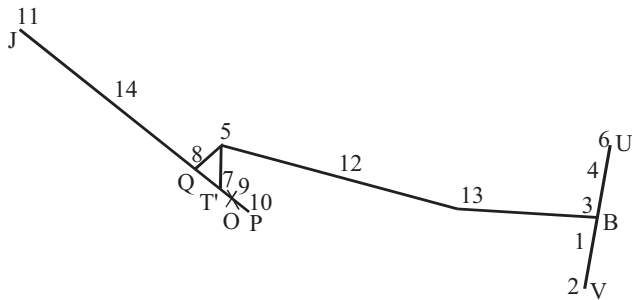
### 4.2. Validation of sensitivity of draught and vertical capacities using the finite element method

In order to validate the calculation [using Eqs. (26)–(29)] of draught  $F_x$  and vertical  $F_z$  capacities provided on the ploughshare, a 3-dimensional (D) FE analysis was performed with ABAQUS FE software.

The 'Maresha' frame model was developed using a 3D discrete rigid wire, planar model (Fig. 5). Each component (part) created was oriented in its own coordinate system and was independent of the other parts in the model. Using the

**Table 1 – Draught, vertical, tangential interfacial and normal interfacial capacities of the plough structure at ploughshare versus pulling angle  $\beta_2 = \alpha$**

		Angle of pull $\alpha$ , degree										
		10	15	20	25	30	35	40	45	50	55	60
Weight of implement and operator's input force are considered	Draught, N	1256	1233	1201	1160	1111	1054	989	917	839	754	664
	Vertical, N	-69	33	134	232	325	414	498	575	646	709	765
	Tangential, N	1210	1155	1092	1022	945	862	773	680	583	482	379
	Normal, N	343	433	518	597	669	735	793	842	884	916	940
Excluding only the effect of implement weight	Draught, N	1256	1233	1201	1160	1111	1054	989	917	839	754	664
	Vertical, N	80	183	284	382	475	564	648	725	796	859	915
	Tangential, N	1161	1106	1043	973	896	813	724	631	534	433	330
	Normal, N	485	575	660	739	811	877	934	984	1026	1058	1082
Excluding only the effect of operator input force	Draught, N	1181	1158	1126	1085	1036	978	914	842	764	679	589
	Vertical, N	60	163	264	362	455	544	626	705	776	839	895
	Tangential, N	1097	1041	979	908	831	748	660	567	469	369	266
	Normal, N	442	532	617	695	768	833	891	941	982	1015	1038
Excluding the effect of operator input force and implement weight	Draught, N	1181	1158	1126	1085	1036	979	914	842	764	679	589
	Vertical, N	210	314	414	512	605	694	778	855	926	989	1045
	Tangential, N	1049	993	930	860	783	700	611	518	420	320	217
	Normal, N	584	674	758	837	910	975	1033	1083	1124	1157	1180



**Fig. 5 – Finite element (FE) model of the structure of the Ethiopian ard plough ‘maresha’, showing the 14 nodal points on the yoke VU, beam BQ, handle JQ and ploughshare QP: O, centroid of ploughshare; T’, point of application of tension by the leather strap/rope on ploughshare.**

assembly module available in ABAQUS software, the geometry of the entire plough was assembled by creating instances of parts, and then positioning the instances relative to each other in a global coordinate system. ABAQUS uses two stages meshing, i.e. seeding the edges of the part instance based on the desired element size or number of elements, and then meshing the part instance. In total, 14 nodes and 14 elements, with element type of linear 3D rigid beam were considered.

In the FEM model, the boundary conditions were applied only on the ploughshare centroid ‘O’, where the draught and vertical forces were assumed to concentrate. The centroid of the ploughshare ‘O’ was constrained to prevent displacements and rotations in all directions. Identical animal pulling force  $F_t$  of 600 N (at  $\beta_2 = \alpha = 10^\circ-60^\circ$ ) and operator’s force  $F_o$  of 150 N (at  $\lambda = 60^\circ$ ) to those forces considered during the traditional force analysis (sensitivity analysis) were applied

for the FE analysis. Thus, concentrated forces were applied at three positions, accounting for forces exerted by the two draught animals and that of the operator. After running the FE analysis, the reaction capacities (draught and vertical capacities) were determined at the ploughshare centroid ‘O’. These capacities could also be translated into normal and tangential interfacial capacities using traditional force balance calculation as a function of the rake angle  $\theta$ .

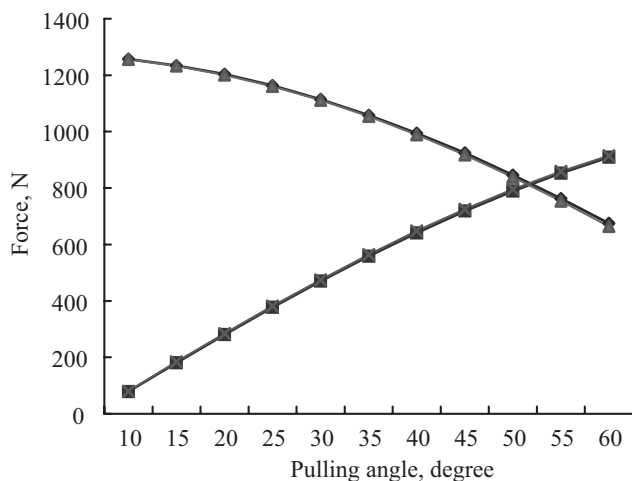
The comparison of traditional force analysis calculation and FE model of draught  $F_x$  and vertical  $F_z$  capacities is given in (Table 2 and Fig. 6). This comparison showed small computational errors of less than 3% and 5% for draught and vertical capacities, respectively, at pulling angles  $\beta_2 = \alpha$  smaller than  $30^\circ$ . Even for larger pulling angles, these errors were still small (Table 2), proving that the traditional force analysis discussed in this study provides accurate estimation of  $F_x$  and  $F_z$ . This encourages using the force analysis of different plough components to establish further conclusions to optimise the structure of the Ethiopian ard plough.

## 5. Conclusions

Mathematical descriptions based on traditional calculations were developed, considering the static analysis of the implement structure of the ard plough at equilibrium condition. The traditional calculations were then verified by means of finite element (FE) analysis and ABAQUS software, with error less than 3% (draught capacity) and 5% (vertical capacity) for working rake angles of  $\leq 30^\circ$ . Based on the existing structure and the parametric relations developed, the

**Table 2 – Comparison of finite element (FE) and traditional calculations of draught and vertical capacities of the plough structure at plough share for different pulling angle  $\beta_2 = \alpha$  (effect of implement weight is excluded)**

Pulling angle $\alpha$ , degree	Finite element calculation		Traditional calculation		Error of draught capacity, %	Error of vertical capacity, %
	Draught capacity $F_x$ , N	Vertical capacity $F_y$ , N	Draught capacity $F_x$ , N	Vertical capacity $F_z$ , N		
10	1257	78	1256	80	-1	2
15	1234	181	1233	183	-1	3
20	1203	281	1201	284	-2	4
25	1163	377	1160	382	-3	5
30	1114	470	1111	475	-3	5
35	1058	558	1054	564	-4	6
40	994	641	989	648	-5	6
45	924	719	917	725	-6	6
50	846	789	839	796	-8	6
55	763	853	754	859	-9	6
60	675	909	664	915	-11	6



**Fig. 6 – Matching between finite element (FE) model and traditional force analysis calculations of capacities provided at the centroid of the ploughshare: ▲, traditional draught capacity ×, traditional vertical capacity; ◆, FE draught capacity; ■, FE vertical capacity.**

following general design considerations and guidelines are foreseen:

- (1) For stable operation, the relation vertical forces should be in equilibrium. For high resistive soil, the operator needs to apply a force on the handle to assist the plough to penetrate soil during tillage process.
- (2) The alignment of the line of pull with the line of pulling of the resultant force acting on the plough body could benefit in minimising impact of bending moment. Such an arrangement decreases the bending moment on the beam so that the beam is subjected mainly to tension and therefore a lighter beam can be used.

- (3) To minimise contacts between the beam and the soil moving along the ploughshare, which increases the draught requirement, the part of the beam nearest to the ground is designed curved. This helps the straight part of the beam to coincide with the line of pulling, a case for which the line of pull coincides with the line of the resultant pulling force.
- (4) The design considered lowering the beam angle to attain minimum draught force requirement so that to increase the draught capacity and thus the efficiency of draught animals.
- (5) The design considered the effect of vibrating of the plough in lateral direction (perpendicular to the travel direction) by the operator to assist soil penetration and reduce the draught requirement. Introducing lateral slot at the juncture of the beam and the handle assembly could lead to comfort operation by the farmer.

The following recommendation can be taken into consideration for further research and improvements of the Ethiopian *ard* Plough:

- (1) The design is to consider the performance in terms of field capacity. The available ploughshare forms a V shape furrow and un-ploughed land is left between parallel neighbouring furrows. Thus, several extra cross-ploughings are required depending on the type of seed to be sown in order to till the whole surface. However, area of interaction between the soil and plough (share and side-wing) should decrease to minimise the friction forces and draught requirement.
- (2) The design is to consider the safety mechanism in case when there are strong roots or stones. This is because, the animals are forced to stop and move back and the farmer has to pull the plough out of the engagement with the object.

- (3) The design takes into account the case of using different animal size/height. Here, the design should allow change of angle of pull to maintain good penetration and stability.

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