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# Multi-Objective Optimization Framework and its Experimental Validation for Bulldozer in Soil Cutting

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ABSTRACT: A multi-objective optimization framework is proposed to generate multiple optimal solutions for the practitioner so that an optimal set of input parameters can be chosen for optimal soil cutting. In this framework power requirement from a bulldozer, the number of passes and time required to cut a fixed volume of soil are minimized simultaneously. The problem is subjected to three constraints, such as limiting the power requirement from the bulldozer, limiting the maximum cutting force on the bulldozer blade and achieving desired the bulldozer production rate. The problem is solved using a multi-objective genetic algorithm. The results show that the Pareto-optimal solutions can be grouped for choosing an optimal set of input parameters for bulldozer and its blade. The framework is validated using the experimental results from the literature.

***Keywords:*** *Multi-Objective Optimization, Genetic Algorithm, Bulldozer, Dozer Blade*

## 1. Introduction

Bulldozer is heavy equipment, which is mainly used for cutting soil. Peurifoy et al. (2006) stated that the soil generates a large amount of resistance due to friction, cohesion, and adhesion between the blade and soil. Many studies have been carried out in the literature for determining the accurate cutting force on the blade. The analytical models have been developed by considering the two-dimensional and three-dimensional failure zones by constructing a soil wedge in the front of the bulldozer blade. Qinsen et al. (1994) and Perumpral et al. (1983) showed that the two-dimensional models are suitable for the wide blades. Reece (1964) proposed the two-dimensional model in which the fundamental equation of earthmoving mechanics was developed, which consists of resistance forces due to shear, cohesion, adhesion, and surcharge pressure. Later, the weights of a soil wedge and inertia force were included into the fundamental equation of earthmoving mechanics by McKyes el al. (1977). Qinsen et al. (1994) determined the cutting force on the wide blade by constructing a soil wedge. Various forces due to cohesion, adhesion and friction were considered. Forces due to the soil pile accumulated in the front of the bulldozer blade were also taken into an account. For the three-dimensional models, a soil wedge with two side crescents is taken into consideration for the narrow blades by Hettiaratchi et al. (1967) and McKyes (1985).

From the above discussion, it is clear that the models have been developed for determining the cutting force accurately by changing a few parameters. However, these models have not been used for making the soil cutting process optimal. Barakat et al. (2017[a]) proposed an empirical based bi-objective optimization formulation for bulldozer and its blade for soil cutting. The cutting force on the blade was minimized, and the volume of soil pile in the front of the bulldozer was maximized. The problem was subjected to limiting the slip ratio. The results showed that the effect of cutting depth of the bulldozer blade did not match well with the cutting force. Later, Barakat et al. (2017[b]) adopted the analytical model of (Qinsen et al., 1994) and proposed a bi-objective optimization formulation for minimizing the cutting force on the bulldozer blade and maximizing the volume capacity of the bulldozer blade with a constraint on power. The proposed bi-objective formulation was successful in generating the Pareto-optimal solutions using a multi-objective genetic algorithm. The important relationships were found among the objectives and decision variables. The study was further extended in (Barakat et al., 2017[c]) wherein two analytical models for quantifying the cutting force on the bulldozer blade were used. The problem was solved using a multi-objective genetic algorithm and a numerical optimization technique using $\varepsilon-$constraint method. The post-optimal analysis was performed to decipher important relationship among the objectives and variables. A guideline was also suggested based on relationships for choosing the best-suited blade for different working conditions.

It is observed that still there is scope for further improving the study of (Barakat et al., 2017[c]) by considering more realistic objectives and constraints. This leads to the motivation of the present study in which the multi-objective optimization framework is proposed for bulldozer and its blade in which power required for cutting soil, the number of passes and time required to cut a fixed volume of soil are minimized simultaneously. More realistic constraints are developed in this paper that are limiting the power required to over the cutting force, limiting maximum force on the bulldozer blade and achieving the desired production rate. Followings are the contributions of this paper.

1. Proposing a multi-objective optimization formulation for an economic and productive soil cutting process.
2. Comprising obtained results with the experimental results for justifying the approach.

The paper is organized into five sections. Section 2 presents the multi-objective optimization framework for soil cutting process. Section 3 presents the multi-objective optimization problem. In Section 4 results are presented and observations are discussed. The paper is concluded in section 5 with a future work.

## 2. Proposed Multi-Objective Formulation

In the proposed optimization framework three objectives are developed, such as minimizing the power requirement from a bulldozer to overcome the cutting force, minimizing the number of passes to finish the soil cutting job, and minimizing the time required to cut soil in one pass so that the blade is completely filled with soil. The minimum power requirement can be viewed as less fuel consumption by a bulldozer that can make the soil cutting process economic. The second and third objectives enhance the productivity of the process by required cutting soil in less time. The objectives are designed using the decision variables on the operating conditions, such as the cutting depth ($D$), the blade cutting angle ($\alpha$), the speed of the bulldozer ($v$), and on dimensions of blade, such as the blade width ($B$), the blade height ($H$), the blade curvature radius ($R$) and the blade curvature angle ($\theta$). The constraints are designed on limiting the remaining power of a bulldozer engine, limiting the cutting force to avoid blade failure, and achieving desired production rate of the process. The formulation for the process is presented in (1).

$$\begin{array}{lll} \text{Minimize} & P, & \text{(Power)}, \\ \text{Minimize} & N, & \text{(Number of passes)} \\ \text{Minimize} & T, & \text{(Time)}, \\ \text{subject to} & P_R \geq 0, & \text{(Power required)}, \\ & F \leq F_{max}, & \text{(Blade failure)}, \\ & P_d \geq P_{d_{min}}, & \text{(Production rate)}, \\ & 0.01 \leq D \leq 0.5, & \text{(Decision variables)}, \\ & 0.785 \leq \alpha \leq 1.309, & \\ & 0.278 \leq v \leq 1.389, & \\ & 3 \leq B \leq 5, & \\ & 1 \leq H \leq 2.5, & \\ & 0.9 \leq R \leq 1.5, & \\ & 1.047 \leq \theta \leq 1.309. & \end{array} \quad (1)$$

The first objective function is minimizing the power required to overcome the cutting force, which is given as,

$$P = Fv \quad (2)$$

where $F$ is the cutting force using Qinsen et al. (1994) cutting force model. The equations are given in the appendix, and $v$ is the bulldozer velocity.The second objective is minimizing the number of passes and it is given as,

$$N = \frac{V_{max}}{V} \quad (3)$$

Here,$V_{max}$ is the maximum volume of soil to be cut and it is assumed to be 200 $m^3$. $V$ is the blade capacity of bulldozer blade as shown in Fig. 1. It is determined as,

$$V = V_1 + V_2 + V_3 + V_4 . \quad (4)$$

These soil pile volumes are calculated as,

$$\begin{aligned} V_1 &= 0.5\mathrm{B}\,(\mathrm{H} + 2\mathrm{D}\tan\varphi_o)^2 \cot\varphi_o\,, \\ V_2 &= 2\mathrm{BD}^2 \tan\varphi_o\,, \\ V_3 &= DBH(\cot\alpha + \cot\beta), \\ V_4 &= 0.5\mathrm{B}\theta R^2 - (0.5R^2 \sin\theta\,). \end{aligned} \quad (5)$$

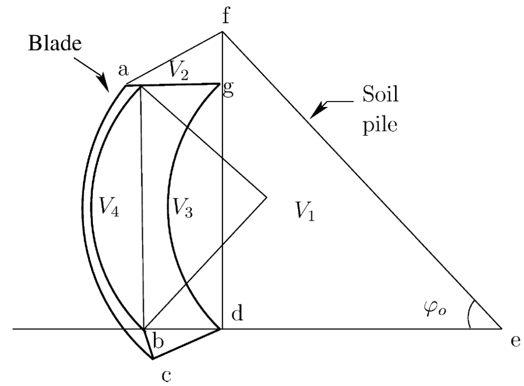


Fig. 1Soil pile volume in the front of a blade.

The third objective is designed as minimizing the time a is given as,

$$T = \frac{L}{v} \quad (6)$$

Here, $L$ is the distance travelled by the blade so that it is completely filled with soil. It is calculated as,

$$L = \frac{V}{BD} \quad (7)$$

The first constraint is developed for the remaining power of bulldozer engine that is given as,

$$\mathrm{P_R} = 0.85\ \mathrm{P_{bull}} - \mathrm{P} \geq 0. \quad (8)$$

It is assumed that efficiency of the engine is 85%.

The second constraint is developed for preventing blade failure during the soil cutting process. The maximum allowed cutting force generated during the soil cutting process is assumed to be $\mathrm{F_{max}} = 300\mathrm{kN}$. The second constraint is given as,

$$\mathrm{F} \leq \mathrm{F_{max}}. \quad (9)$$

The third constraint is designed on the production rate of the soil cutting process. The production rate is defined as the maximum volume of soil cut by the bulldozer blade per pass per unit time that is given as,

$$\mathrm{P_d} = \frac{\mathrm{V}}{\mathrm{T}} \quad (10)$$

The third constraint is developed such that the production rate should be greater than $\mathrm{P_{d_{min}}}$ that is given as,

$$\mathrm{P_d} \geq \mathrm{P_{d_{min}}}. \quad (11)$$

A small value of $P_{d_{min}} = 0.008$ cubic meter per second is chosen.

## 3. Multi-Objective Evolutionary Algorithm

In this paper, a benchmark multi-objective evolutionary algorithm is used which is known as NSGA-II or elitist non-dominated sorting genetic algorithm proposed by Deb et al. (2001). It is a meta-heuristic population-based algorithm which first initializes random population. The fitness is then assigned by the Pareto-ranking and crowding distance operators. The non-dominated solutions are grouped as front-1 and other solutions are grouped in different fronts. The crowding distance operator is used to maintain diversity among the same ranked solutions. In the loop of generation, good and above average solutions are selected using the crowded binary tournament operator in which two solutions are selected at random. A solution with better rank is selected over other. If both solutions have the same rank, then a solution with larger crowding distance value is selected. In case of a tie, any solution is selected randomly. Simulate binary crossover operator and polynomial mutation operator are used for variation in the population. The environment selection is then performed in which a combined population is constructed from the last generation population and the newly created population. The best solutions are chosen from the combined population to fill the next generation population. The solutions from front-1 are copied first followed by other fronts. If the size of the last front, that to be included in the next generation population, is more than the remaining size of the next generation population, then solutions are copied one-by-one based on their larger crowding distance value. This completes one generation of NSGA-II.

## 4. Simulation Results and Discussion

A few parameters of NSGA-II are kept constant, that are, the population size (=100), a maximum number of generations (=200), crossover probability (=0.9), distribution index for crossover (=15), mutation probability (=0.333), distribution index for mutation (= 20). A mid-stiffness clay soil (Jack et al. 1985) is considered and its physical parameters are given as, the density of uncut soil $\gamma_o$=640.74kg/m$^3$, the density of cut soil $\gamma$=640.74 kg/m$^3$, the cohesion of uncut soil $C_o$=1019.715N/m$^2$, the cohesion of cut soil $C$ = 2039.43N/m$^2$, the soil adhesion factor $A_d$ = 0 N/m$^2$, the angle that the rapture plane makes with horizontal $\beta$ = 23 (radians), the angle of accumulation of cut soil $\varphi_o$ = 30 (radians) and angle of internal friction of soil $\varphi$ = 27 (radians). The flywheel power is rated at $P_{bull}$ = 227.438 kNm/s.

### 4.1 *Obtained Pareto-optimal solutions*

The Pareto-optimal solutions for the given multi-objective problem are shown in Fig. 2. It can be seen that the solutions are grouped that are referred as 'Surface solutions', 'Surface-knee solutions', 'Knee solutions' and 'Extension solutions'. The 'Surface solutions' are corresponding to lower power requirement. In this group, a wide-range of solutions for other two objectives can be seen. In the same surface 'Surface-knee solutions' are also shown. Outside the 'Surface-knee solutions' a marginal gain in number of passes can drastic increase time, or vice-versa. Therefore, a practitioner can choose any solution with less power requirement from the set of 'Surface-knee solutions'. The other group of solution is the knee solutions. It can be seen that gain in one objective can drastically hamper the other objectives for solutions lying away from the knee-solutions. Therefore, the knee region solutions are always preferable to the decision-makers and practitioners. The last group is the 'Extension solutions' in which solutions are evolved in a line. These solutions are corresponding to higher power requirement but with lower time and number of passes.

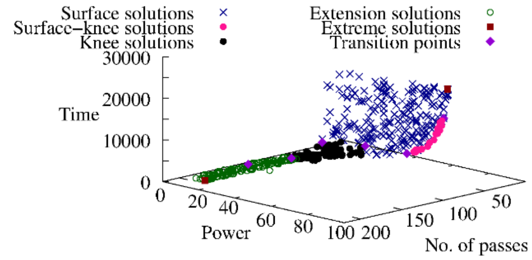


Fig. 2 The obtained Pareto optimal solutions

### 4.2 *Experimental validation of framework*

King et al. (2011) compared various cutting force models on two-types of soil with the experimental cutting force. For validating the multi-objective framework, NSGA-II is run for the given set of parameters for soil, blade, and bulldozer which are given as, $\gamma_o$=700kg/m$^3$, $\gamma$=1000kg/m$^3$, $C_o$=700N/m$^2$, $C$ = 1400 N/m$^2$, $A_d$ = 39 N/m$^2$, $\beta$ = 35 (radians), $\varphi_o$ = 30 (radians), $\varphi$ = 30 (radians). $\delta$ = 17 (radians), $H$ = $D$+0.1(m), $R$ =10000(m), $B$=0.0127(m), $\theta$=0.001(radians), $\alpha$=89 (radians), $v$ = 0.0033(m/s).

It can be seen from Fig. 3 that the cutting force of the Pareto-optimal solutions shows a closer agreement with the experimental cutting force found in King et al. (2011). The behavior is the also same which was also observed in King et al. (2011).

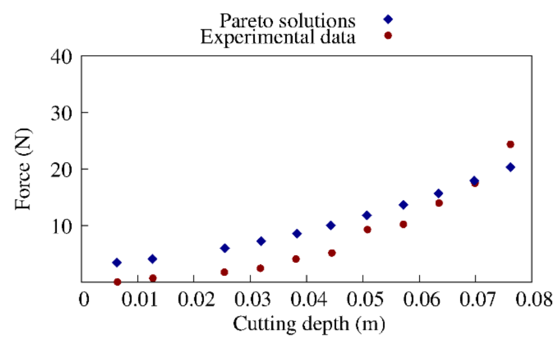


Fig. 3. The cutting forces values of obtained Pareto-optimal solutions and the experimental data.

## 5. Conclusions

In this paper, a multi-objective optimization framework was proposed with three realistic objectives and three problem-specific constraints using seven decision variables. The problem was solved using NSGA-II. The framework was also validated with the experimental results from the literature. It can be concluded that the same framework can be used to obtain an optimal set of input parameters based on the obtained Pareto-optimal solution for optimal soil cutting. In the future work, the given formulation can be extended to more problem-specific objectives and constraints such that variation in geometry of the blade can be incorporated.

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## Appendix

*Model of Qinsen et al. (1994) for Cutting Force on Wide Blade*

1. The forces generated by the soil pile moving on the ground

(a) Weight of the soil pile on the ground is given as,

$$m_1 g = \frac{1}{2}\gamma_o B(H + 2D \tan\varphi_o)^2 \cot\varphi_o. \tag{12}$$

(b) Frictional force between the soil pile and the ground is given as,

$$F_{f1} = m_1 g \tan\varphi. \tag{13}$$

(c) Cohesion force between the soil pile and the ground is given as,

$$F_{c1} = C_O B(H + 2D \tan\varphi_o). \tag{14}$$

2. The forces generated by the cut soil sliding up between the blade and the soil pile

(a) Frictional force between the cut soil and soil pile is given as,

$$P_{f1} = (F_{f1} + F_{C1}) \tan\varphi. \tag{15}$$

(b) Cohesion force between the cut soil and soil pile is given as,

$$P_{c1} = C_O BR\theta. \tag{16}$$

(c) Adhesion force between the cut soil and blade is given as,

$$P_{ad} = A_d BR\theta. \tag{17}$$

(d) Frictional force between the cut soil and blade is given as,

$$P_{f2} = (F_{f1} + F_{C1}) \tan\delta. \tag{18}$$

(e) Weight of the cut soil sliding upon the surface of blade is given as,

$$m_2 g = 2\gamma_O BHD. \tag{19}$$

3. The forces generated on the sides of soil wedge

(a) Force acting normal to the faces (bcd) and (nmk) of the soil wedge is calculated as,

$$G = \frac{1}{6}\gamma D^3(1 - \sin\varphi)(\cot\alpha + \cot\beta). \tag{20}$$

(b) Frictional force on the sides (bcd) and (nmk) of the soil wedge is calculated as,

$$SF_2 = G \tan\varphi. \tag{21}$$

(c) Cohesion force on the sides (bcd) and (nmk) of the soil wedge is calculated as,

$$CF_2 = \frac{1}{2}CD^2(\cot\alpha + \cot\beta). \tag{22}$$

4. Other forces on the soil wedge

(a) Weight of soil wedge,

$$m_3 g = \frac{1}{2}\gamma BD^2(\cot\alpha + \cot\beta). \tag{23}$$

(b) Adhesion force between the soil and cutting edge of the blade is given as,

$$F_{ad} = \frac{A_d}{\sin\alpha} BD. \tag{24}$$

Thus, the force acting normal to the face (bdkn) of the soil wedge is calculated as,

$$W = P_{f1} + P_{f2} + P_{ad} + m_2 g + m_3 g. \tag{25}$$

5. Forces on the rupture plane

(a) Cohesion force on the rupture plane is calculated as,

$$CF_1 = \frac{C}{\sin\beta} BD. \tag{26}$$

(b) Frictional force on the rupture plane is calculated as,

$$SF_1 = Q \tan\varphi. \tag{27}$$

The force acting on the cutting edge of the blade is given as, The horizontal component of the resultant force acting on the blade is determined as,

$$F_x = P_r \sin(\alpha + \delta) + F_{f1} + F_{c1}. \tag{29}$$

$$P_r = (W \sin(\beta + \varphi) - F_{ad} \cos(\alpha + \beta + \varphi) + 2\,SF_2 \cos(\varphi) + 2\,CF_2 \cos(\varphi) + CF_1 \cos(\varphi)) / \sin(\alpha + \beta + \varphi + \delta) \tag{28}$$

The vertical component of the resultant force acting on the blade is determined as,

$$F_y = P_r \cos(\alpha + \delta) - (P_{f2} + P_{ad}). \tag{30}$$

Therefore, the resultant cutting force on the blade is calculated as,

$$F = \sqrt[2]{F_x^2 + F_y^2}. \tag{31}$$