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ORIGINAL PAPER

Efficient Cable Shovel Excavation in Surface Mines

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Abstract The cable shovel is widely used in surface mining. High operating and ownership costs necessitate efficient use of the cable shovel. Operator practices have long been suspected to contribute towards the inefficient use of the shovel. Crowd arm and hoist rope speeds are key measures of operator practices. The objective of this work is to find the crowd arm and hoist rope speeds for *optimal* shovel performance for given initial conditions and material properties. Shovel kinematics and dynamic modeling, using shovel geometry and the simultaneous constraint method, respectively, have been employed to build models of the excavation process. Dynamic models of the shovel payload and the material cutting resistance have also been developed using geometric simulation and passive soil pressures techniques, respectively. These models are solved numerically by combining Runge–Kutta and Gaussian elimination algorithms to compute the work done and the resistive forces during shovel excavation. The algorithms have been combined into a shovel simulator. The simulator has been used to simulate the P&H 2100BL shovel. The simulation results indicate that input energy and digging time increase with increasing crowd arm and decreasing hoist rope speeds. The input energy per unit loading rate is proposed as an appropriate measure of shovel performance. High energy per unit loading rate occurs for high crowd speeds and low hoist rope speeds. For the simulated conditions and crowd arm and hoist rope speeds ranging from 0.25 to 0.5 ms^{-1} and 0.5 to 0.7 ms^{-1}, respectively, the optimal crowd arm and hoist rope speeds were found to be 0.25 ms^{-1} and 0.7 ms^{-1}, respectively, and the objective function value was 0.21 KJs/kg. This work establishes, theoretically, the fact that operator practices have an effect on shovel performance and is useful in establishing optimum practices. The results are the initial steps towards full automation of the excavation process.

Keywords Cable shovel performance · Energy efficiency · Dynamic simulation · Excavation modeling · Kinematics · Dynamics

List of symbols

R_i	Vector for link i with magnitude r_i and direction θ_i
s_i, c_i and t_i	sin θ_i, cos θ_i, and tan θ_i

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α_i and ω_i	Angular acceleration and velocity of link i, respectively
M_4	Mass of crowd arm
A_{c4x} and A_{c4y}	Components of acceleration of crowd arm center of mass
I	Moment of inertia of crowd arm about center of mass
C_x and C_y	Components of crowd force
H_x and H_y	Components of hoist force
N_x and N_y	Components of normal force
α_c	Bucket teeth cutting angle
v	Internal angle of bucket (90° if bucket is assumed to be cuboid)
E	Input energy
$\dot{r}_i$ and $\ddot{r}_i$	First and second derivative of link length with respect to time

1 Introduction

The cable shovel is widely used in surface mine excavation due to its ruggedness, high productivity, high breakout forces and longevity. The efficient use of the shovel is required to minimize ownership and operating costs. Consequently, mine planning engineers and managers put emphasis on the efficient use of cable shovels. It has long been known that operator practices can lead to inefficient use leading to increased downtimes resulting in high maintenance costs. In spite of this understanding, there is a lack of comprehensive theoretical models of cable shovel excavation that permit objective assessment of operator practices. Cable shovel dipper motion is achieved by moving the crowd arm and hoist ropes. In this research, the speeds of the crowd arm and hoist ropes are used as the measure of operator practices. The objective of this work is to provide models to determine *optimal* operator practices and thus provide an understanding of the impact of operator practices on shovel performance. This work however, is limited to an assessment of the digging process and does not include the swing and propel motions.

Cable shovel kinematics and dynamic models have been developed to describe the digging process. Dynamic material weight and cutting resistance models have also been promulgated to constitute a comprehensive description of the process encompassing both the machine motion and its interaction with the operating environment. The dynamic payload and cutting resistance models employ geometric simulation techniques and a modified Balovnev (1983) model respectively. In assessing the performance of a cable shovel, the measure of performance should focus on resistant forces, digging cycle time and the material produced (payload). The energy per unit loading rate required to overcome the resistant forces is directly proportional to the resistant forces and digging time but inversely proportional to the payload. Consequently, decreasing the energy per unit loading rate decreases the undesirable whilst increasing the desirable factors. Consequently, the energy per unit loading rate was used as the measure of shovel digging performance. This work is unique as it presents a comprehensive theoretical description of the cable shovel digging process in a computationally efficient model. The inputs are different from that in previous work and are more relevant in assessing operator impact on efficiency. This work introduces a pioneering, practical approach to assessing operator performance which can be immediately put to use by mining engineers.

2 Cable Shovel Excavation

The cable shovel (Fig. 1) executes four primary motions—propel, swing, hoist and crowd/retract. During the digging cycle only the hoist and crowd/retract motions are executed in a 2-D plane. There have been attempts to describe the kinematics and dynamics of cable shovel digging motion using the Newton–Euler formulation (Daneshmend et al. 1993; Vaha and Skibniewski 1993; Frimpong et al. 2003, 2005). All these attempts, however concentrate only on describing the kinematics and dynamic parameters responsible for given trajectories. All trajectory optimization attempts have been empirical lacking rigorous theory (Karpuz et al. 1992; Maciejewski and Jarzebowski 2002). Even though the Newton–Euler formulation is employed in the authors' previous work (Frimpong et al. 2005) in detailed analysis of the kinematics and dynamics of the cable shovel, the simultaneous constraint method[1] used in this work is computationally more efficient for the large number

[1] For a detailed discussion on the simultaneous constraint method, also referred to as modeling as particles (Haug 1989), refer to the works by Haug (1989 and 1992) and Gardner (2001).

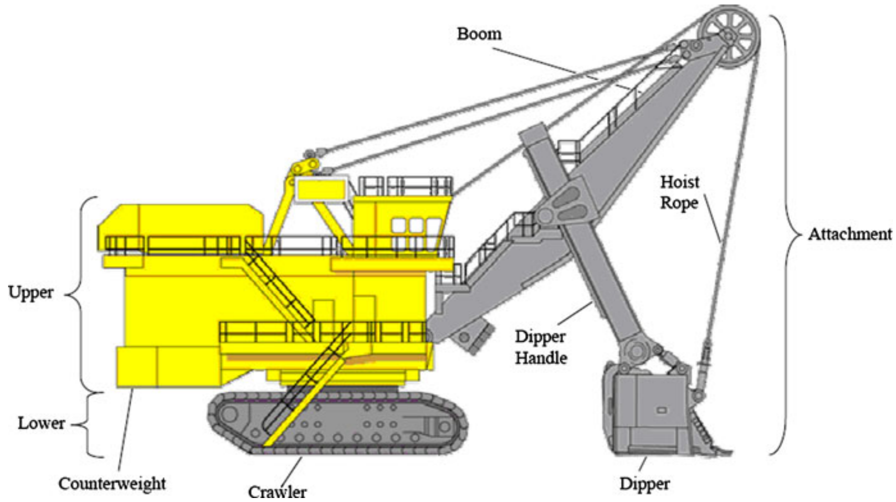

Fig. 1 Nomenclature of cable shovel (P&H Mining, 2003)

of replications required in the optimization work. Also, previous work does not pay critical attention to the modeling of cutting resistance and payload is completely ignored.

2.1 Kinematics

Figures 2 and 3 show a schematic representation of a cable shovel and its kinematics, respectively. Equation 1 is the vector loop equation whereas Eq. 2 is the same equation in component form. By double differentiating with respect to time, the acceleration equation for the kinematics is obtained as Eq. 3.

$$R_1 + R_2 = R_3 + R_4 \tag{1}$$

$$\begin{bmatrix} r_1 \cos\theta_1 + r_2 \cos\theta_2 \\ r_1 \sin\theta_1 + r_2 \sin\theta_2 \end{bmatrix} = \begin{bmatrix} r_3 \cos\theta_3 + r_4 \cos\theta_4 \\ r_3 \sin\theta_3 + r_4 \sin\theta_4 \end{bmatrix} \tag{2}$$

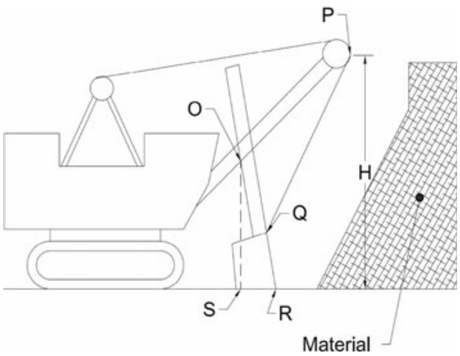

Fig. 2 Schematic representation of cable shovel

2.2 Dynamics

The dynamic modeling involves the development of the force constraint equations. These are given by

$$\begin{bmatrix} (r_3 s_3 - r_2 s_2) & r_4 s_4 \\ (r_3 c_3 - r_2 c_2) & r_4 c_4 \end{bmatrix} \begin{pmatrix} \alpha_3 \\ \alpha_4 \end{pmatrix} = \begin{pmatrix} (c_2 r_2 \omega_3 - c_3 r_3 \omega_3 - 2 s_3 \dot{r}_3)\omega_3 - (c_4 r_4 \omega_4 + 2 s_4 \dot{r}_4)\omega_4 + c_3 \ddot{r}_3 + c_4 \ddot{r}_4 \\ (s_3 r_3 \omega_3 - s_2 r_2 \omega_3 - 2 c_3 \dot{r}_3)\omega_3 + (s_4 r_4 \omega_4 - 2 \dot{r}_4 c_4)\omega_4 - s_3 \ddot{r}_3 - s_4 \ddot{r}_4 \end{pmatrix} \tag{3}$$

In arriving at Eq. 3, one must realize the relationship established by Eq. 4.

$$\theta_2 = \theta_3 - \frac{2\pi}{3} \qquad \Rightarrow \omega_2 = \omega_3 \tag{4}$$

Eqs. 5–7. Equation 7 represents the direction constraint of the forces.

$$\sum F_x = M_4 A_{c4x} \qquad \sum F_y = M_4 A_{c4y} \tag{5}$$

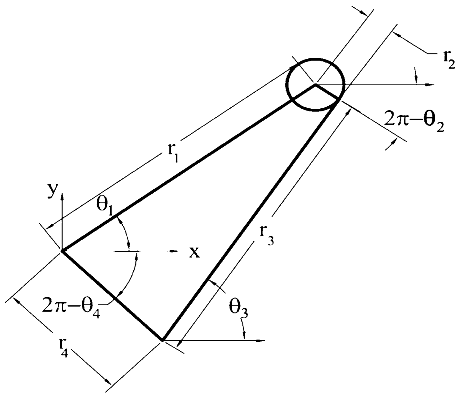

Fig. 3 Cable shovel kinematics

$$\sum M = I\alpha_4 \tag{6}$$

$$\frac{C_y}{C_x} = \tan(2\pi - \theta_4)$$
$$\frac{H_y}{H_x} = \tan\theta_3 \tag{7}$$
$$\frac{N_y}{N_x} = \tan\left(\theta_4 - \frac{3\pi}{2}\right)$$

Equation 8 shows the acceleration characteristics of the center of mass of the crowd arm.

$$\begin{aligned} A_{c4x} &= -r_{c4}\omega_4^2 c_4 - 2\dot{r}_4\omega_4 s_4 + \ddot{r}_4 c_4 - (r_{c4}s_4)\alpha_4 \\ A_{c4y} &= -r_4\omega_4^2 s_4 + 2\dot{r}_4\omega_4 c_4 + \ddot{r}_4 s_4 + (r_{c4}c_4)\alpha_4 \end{aligned} \tag{8}$$

By combining Eqs. 3–8 a system of 10 equations with the variables defined by x in Eq. 9. Consequently, by solving this system the solution for x is determined. The solution procedure is discussed in Sect. 3.

$$x = [A_{c4x} \quad A_{c4y} \quad \alpha_3 \quad \alpha_4 \quad C_x \quad C_y \quad H_x \quad H_y \quad N_x \quad N_y]^T \tag{9}$$

2.3 Digging Resistant Forces

Hemami et al. (1994) shows that the resistance to digging by a shovel dipper can be described completely by 6 forces and that the cutting resistance, the dipper weight and the payload weight are the most significant for most mining applications. The dynamic payload weight model presented by Awuah-Offei and Frimpong (2004) is used in this work. Balovnev (Balovnev 1983) applied the passive earth theory to compute the cutting resistance on a right-angled framed assembly. The Balovnev (1983) model has been modified to take into account bucket teeth and its configuration which has been shown to reduce the cutting resistance by as much as 30% (Zelenin et al. 1986). This was achieved by inculcating the reduction factors published by Zelenin et al. (1986). Also, the Balovnev (1983) model would not be applicable to computing dynamic cutting resistance unless a means is provided to solve for the dynamic cutting angle. The cutting angle is given by Eq. 10.

$$\alpha_c(t) = \theta_4(t) + v - 2\pi \tag{10}$$

2.4 Energy per unit loading rate

The solution for the models described above provides the dynamic crowd and hoist forces. Since the velocity of the crowd arm in the direction of both the crowd and hoist forces are known, the dynamic energy can be computed from Eq. 11. The energy per unit loading rate is then given by Eq. 12.

$$\mathrm{E} = \int_0^t (\mathrm{Force} \times \mathrm{velocity})dt \tag{11}$$

$$\text{Energy per unit loading rate, } \widehat{\mathrm{E}} = \frac{\mathrm{E} \times \text{Digging Time}}{\text{Payload}} \tag{12}$$

3 Numerical Modeling

The system of equations, a differential–algebraic equation (DAE), is the main engine driving the dynamic simulation of the cable shovel. This is because r_i, $\dot{r}_i$, $\ddot{r}_i$, θ_i, ω_i and α_i are time dependent terms which appear in the linear system of equations. The solution approach is to obtain the value of the time-dependent variables from an ODE solver first. Concurrently, at each iteration step the values of these time-dependent variables are used to constitute the linear system and solved. A Runge–Kutta (4, 5) embedded algorithm with automatic step-size control is used to solve the ODEs to obtain values for the time-dependent variables given initial conditions. The linear system is solved by Gaussian elimination with partial pivoting. This solution algorithm is capable of solving for all conditions of the cable shovel simulation except for: (1) cases where the crowd arm is extended to its maximum limit; and (2) cases where $\theta_1 - \theta_4 + 2\pi < 0$. In the first instance, the methodology employed is to exit the program, reformulate the system and use the final condition as the initial condition for the second phase of the solution. The second condition represents the scenario where the crowd arm has rotated past the boom, a physically impossible solution state. MATLAB/SIMULINK (The Mathworks Inc 2004) platform is used to build the model. This is because of the wide variety of numerical routines already programmed in MATLAB.

4 Numerical Example

The optimization scheme has been run for the P&H 2100BL shovel with the data shown in Table 1. The data has been modified for proprietary reasons. The simulated soil conditions (Table 2) represents average surface mine overburden conditions in in-situ digging. The crowd arm and hoist rope speeds are assumed to be constant during the digging cycle (Hendricks et al. 1989). The simulation was carried out for crowd arm and hoist rope speeds ranging from 0.25 to 0.5 ms^{-1} and 0.5 to 0.7 ms^{-1}, respectively in steps of 0.01 constituting 546 replications. In the event that the maximum crowd arm length is reached, the crowd arm speed is set to zero (this is one of several operating options). The objective was to find the optimal (lowest energy per unit loading rate) combination of crowd arm and hoist rope speeds (Fig. 4).

Table 2 Soil input data from Suministrado et al. (1990)

Soil parameter	Value
Soil-metal friction angle [radians]	0.6747
Internal friction angle [radians]	0.5105
Angle of repose (assumed)	60°
Bulk density [tonnes/m^3]	1.45
Unit weight [KN/m^3]	14.255
Cohesion [KN]	9
Material swell factor (assumed)	1.25

5 Results and Discussions

Figures 5–8 show the results of the simulations. Figure 5 shows the digging times for various crowd and hoist speeds as a contour plot. Digging time decreases with decreasing crowd arm speed and increasing hoist rope speeds. As shown in Fig. 6, this is due to the *deeper* cuts taken by higher crowd speeds and the *shallower* cuts by increasing hoist speeds. The 'ridge' running across the plot represents the region where the transition between a single trajectory and a complex trajectory resulting from the crowd arm reaching the limit of the effective length (see Fig. 6). Figure 7 shows the total input energy required to overcome the resistance to digging and machine motion. The energy decreases with increasing hoist speed and decreasing crowd speed.

The fact that the total energy appears to decrease with increasing hoist speed seems to contradict Eq. 11. The total energy for higher hoist speeds

Table 1 Modified shovel input data for P&H 2100BL

Data Type	Parameter	Value
Dipper dimensions	Bucket capacity [m^3]	12.997
	Bucket weight [kg]	21,205
	Lip to latch keeper (front) [m]	2.78
	Bucket inside width [m]	2.74
	Bucket internal angle υ	90°
	Bucket fill factor	0.95
Initial position parameters	Boom length [m]	15.24
	Boom sheave radius [m]	1.04
	Boom point sheave height (H) [m]	15.57
	Boom angle	45°
	Effective crowd arm length [m]	8.84
	x-coordinate of starting point [m]	4
	y-coordinate of starting point [m]	0

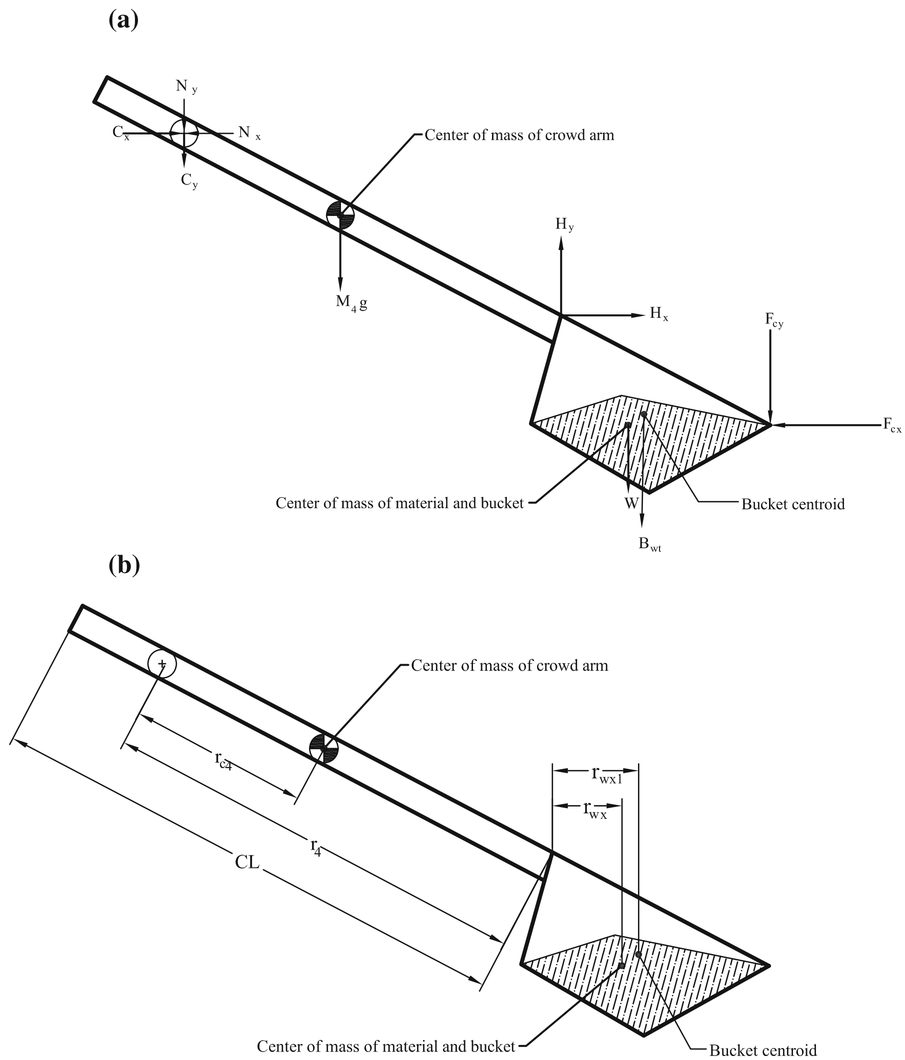

Fig. 4 Free body diagram of crowd arm and dipper assembly: **a** forces; **b** dimensions

decreases because the digging cycles are shorter saving on energy even though power consumption is higher.

Figure 8 shows the objective function of the optimization problem, energy per unit loading rate. The objective function decreases with increasing hoist speed and decreasing crowd speed. This means the optimal operator practice is to move the dipper at low crowd speeds and high hoist speeds. Within the domain of this particular example, the optimal trajectory will be produced by a crowd arm speed of 0.25 ms^{-1} and a hoist rope speed of 0.7 ms^{-1} and the objective function value is 0.21 KJs/kg. The trajectory resulting from this operating strategy is shown in Fig. 6. Even though only 3 trajectories are shown here it is easy to see that this was the *shallowest* trajectory. This result is consistent with the observation of Hendricks et al. (1989) that shovel performance decreased with increased depth of cut.

6 Conclusions

Operator practices have been a long standing problem in maximizing the return on the investment in a cable shovel. In this work, crowd arm and hoist rope speeds have been used as tangible measures of operator practices and the energy per unit loading rate the measure of shovel performance. The objective then, was to minimize the energy per unit loading rate

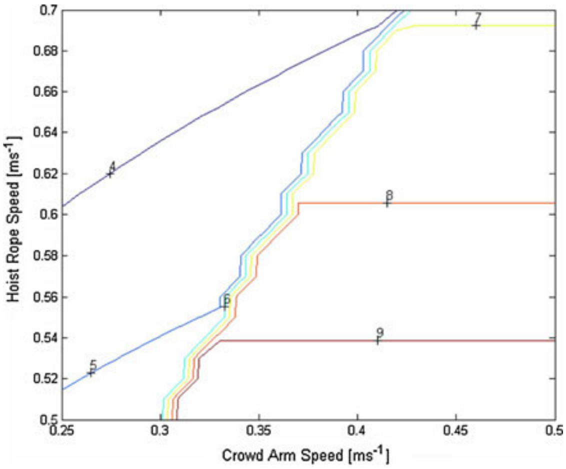

Fig. 5 Digging time [secs]

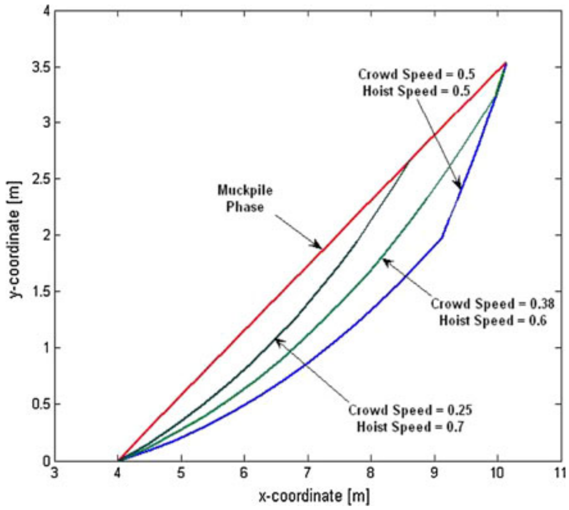

Fig. 6 Sample trajectories

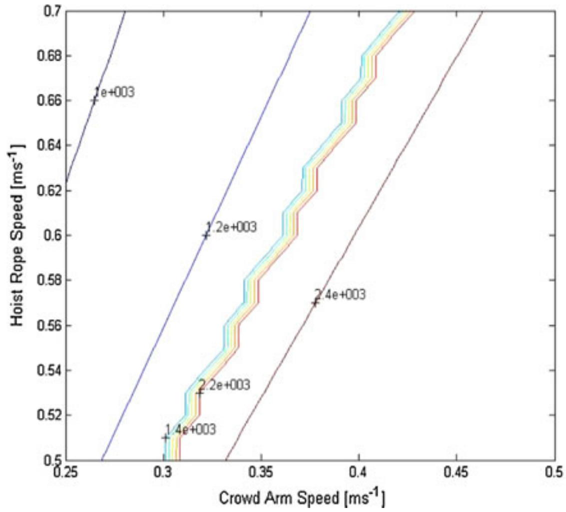

Fig. 7 Total input energy [kJ]

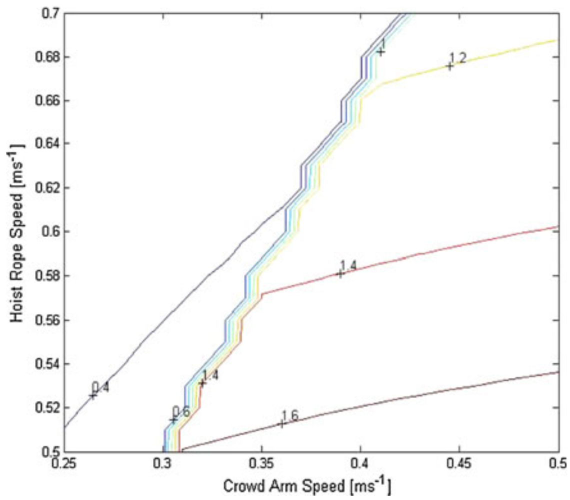

Fig. 8 Energy per unit loading rate [kJs/kg]

given a range of crowd arm and hoist rope speeds. Cable shovel kinematics, dynamics, dynamic payload and cutting resistance models have been successfully formulated to build a shovel simulator in MATLAB/SIMULINK (The Mathworks Inc 2004). The simulator was run for 546 replications for crowd arm and hoist rope speeds ranging from 0.25 to 0.5 ms^{-1} and 0.5 to 0.7 ms^{-1} respectively in steps of 0.01. The optimal operating trajectory is produced by moving crowd arm and hoist rope at speeds of 0.25 and 0.7 ms^{-1}, respectively. The optimal specific energy per unit loading rate is 0.21 KJs/kg. It is also shown that cable shovels perform better for lower depths of cut resulting from lower crowd arm speeds and higher hoist rope speeds. Implementing this operating scheme will result in reduced energy and maintenance costs (since the resistance to digging reduces) without reducing productivity (loading rate).

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