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Economic Excavator Configuration for Earthwork Scheduling

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Abstract- *Excavating processes performed frequently in building, civil and infrastructure projects are critical and costly. To define a cost-effective excavator configuration, an earthwork planner depends mostly on experience and intuition. This paper presents a computational system called the Economic Excavator Configuration System, which selects the most favorable configuration of a heavy-duty excavator according to the earthwork package and its job conditions. This system instructs the earthwork manager in the best-fit excavator configuration for profitable operation by considering the implicit constraints and conditions exhaustively. The system identifies the best-fit PDFs of the process completion time and that of the total profit, given an excavator configuration. A test case, which was performed at a building basement excavating project, confirmed the usability and validity of the method.*

I. Introduction

Excavating, which initiates processing entity (i.e., a rock-earth volume) in an earthwork operation, requires hydraulic heavy-duty excavators. They include front shovel, back shovel (or hoe, backhoe), loader, and specialty which need a great financial investment. A backhoe is used for digging below track level such as pits for basement. It is a boom and stick downward swing machine mounted on either crawler or pneumatic-tire with many different working attachments and engine configurations. Eco-economic performance of a hoe varies with the configuration of machine attributes given an earthwork package. The best-fit configuration of machine attributes which maximize the total profit of the excavating process can be identified by considering the work package information and other attributes involved in soil, job site, and management all together. In order to assure the most favorable cost productivity, the cash inflow and outflow items, which are subject to the transitory nature of operating conditions on a job site, should be considered.

Fuel and oil consumption take up a big portion of the cost in excavating jobs. For sure, saving fuel consumption is an important issue for reducing process completion cost and alleviating environmental burden. Identifying the most favorable machine configuration involves many different source of data, and sophisticated and repetitive computations using these sources. They include the earthwork control account information under study; excavator database of which each record maintains a maximum digging depth, a maximum dumping height, engine capacity, and a set of buckets attachable; the historical performance data of each equipment including its fuel and oil consumption amount; job site conditions; and work characteristics, etc. Indeed, it is time consuming, error prone, and expensive to collect this entire information from many different sources in time and to identify the optimal solution by manual basis depending on intuitive gut feeling. It may take easily several hours for a well experienced earthwork manager to complete the entire data compiling and decision process.

In order to increase the eco-economic performance, the values of the attributes that influence an excavator's cost productivity should be determined and analyzed in real time. Earthwork management tools can be strengthened by introducing a computational method that collects and analyses the values of the attributes that influence an excavator's internal and external system variables that influence an excavator's eco-economic performance negatively records the data into a database; computes swiftly the cycle time and the time, cost and profit performance of each excavator configuration of engine, maximum digging depth, and bucket configuration; identifies the optimal machine configuration; and handles the variability of the process completion time and that of the process completion profit with the configuration. Thus, such a method may provide a tool to control economic excavating and fuel efficiency.

II. Economic Excavator Configuration System

The system implements the stochastic time-profit tradeoff analysis into its system. The method described below was coded by using MATLAB for improving the usability of the computational method in eco-economic excavator operation practice. The method identifies the most favorable combination of maximum digging depth, engine capacity (HP), bucket size, and the timing when fuel saving mode should start. It implements an excavating operation plan which maximizes expected profit by using the optimal configuration.

2.1 Defining Work Package, Excavator, and Attachment Attributes

The system reads the earthwork package's control account information (i.e., the unit price commissioned in \$/M^3-BM(C_u), target duration in days (D_T), daily working hours (H_D), average digging depth in feet (H_A), soil type (S_T), and total volume of work in bank measure M^3 (V_T)) from a matrix W_P. The C_u, D_T, H_D, and V_T are obtained from contract documents; the H_A and the S_T are from earthwork manager. The S_T, which is associated with the bucket fill factor (f_F), is classified according to Das (2011).

$$W_p = |30 \quad 5 \quad 8 \quad 5 \quad 'Common\ earth' \quad 2{,}000| \qquad (1)$$

Given the value of soil type S_T (i.e., *Common Earth*), the value of f_F is obtained from matrix M_S shown in Eq.2 of which each column denotes soil type (S_T) and the range of bucket fill factor (i.e., [100; 110]). Then, system sets its probability density function (i.e., f_F=*uniform (100,110)*).

$$Ms = \begin{vmatrix} Bank\ clay & 100{:}110 \\ Common\ Earth & 100{:}110 \\ Rock - Earth\ mixture & 105{:}115 \\ Rock - poorly\ blasted & 85{:}100 \\ Rock - well\ blasted & 100{:}110 \\ Shale & 85{:}100 \\ Sandstone & 85{:}100 \\ Standing\ bank & 85{:}100 \end{vmatrix} \qquad (2)$$

Given the excavator name (E_N), maximum digging depth (H_M), and maximum loading height (H_{ML}), system creates a query in structured query language (SQL), queries the equipment database, and retrieves the available excavators' attributes (i.e., equipment ID (E_{ID}), engine type (E_T; 1=gasoline, 2=diesel), average hourly fuel consumptions in idle(A_F^i), low(A_F^l), medium(A_F^m), high(A_F^h), and accelerated (A_F^a) states (l/hour), hourly cost of owning(C_F), hourly cost of operating(C_V) (\$/hour), maximum digging depth(H_M), maximum loading height(H_{ML}), engine capacity(HP), and the series of buckets (B_s) attachable to each and every backhoe along with their hourly cost). For example, given that E_N, H_M, and H_{ML} are 'Backhoe', '13ft', and '14ft', respectively, the method executes the SQL statement shown in Eq.3. Then, it saves the returned dataset (i.e., E_{ID}, E_T, A_F^i, A_F^l, A_F^m, A_F^h, A_F^a, C_F, C_V, H_M, H_{ML}, and *HP*) in equipment matrix E_q and the buckets with hourly cost in matrix B_s. Each backhoe may attach a bucket from different size of buckets. For example, the buckets of CAT 320 come in various sizes, ranging from 0.72cy to 2.08cy nominal capacity. The number of backhoes available (i.e., *n=length* (E_q)) and the number of buckets attachable to a backhoe (i.e., *m=length* (B_s)) are 8 and 6, respectively. Given the easiness to load the material (E_L) by the equipment operator in the percentage value of [30:50%], which may be a lower value for easy-to-load materials (i.e., loam, sand, or gravel, etc.); a higher value for hard-to-load materials (i.e., sticky clay or blasted rock, etc.) according to Nunnally (2006), system saves the values of E_L into computer memory.

$$\begin{array}{ll} SELECT & E_{ID}, E_T, A_F^i, A_F^l, A_F^m, A_F^h, A_F^a, C_F, C_V, H_M, H_{ML}, HP \\ FROM & 'ExcavatorTable' \\ WHERE & 'E_N = Backhoe' \,\&\&\, 'H_M \geq 13m' \,\&\&\, 'H_{ML} \geq 14m' \end{array} \qquad (3)$$

2.2 Defining Job Site and Work Characteristics

The job efficiency factor involves job conditions (C_J) (i.e., the haul road, the loading floor, the surface and weather condition in the cut, the variability in the depth of cut, and truck spotting on one or both sides, topography etc.) and management conditions (C_M). The method either makes use of the job efficiency factor matrix E_F provided by Nunnally (2000) and Peurifoy et al. (2006) or the fuzzy inference system (FIS) which effectively handles the vagueness, fuzziness, and uncertainty of the input variables. Each column and row of E_F represents excellent, good, fair, and poor job conditions and management conditions, respectively.

Given the soil type (S_T) defined the value of earth volume conversion factor (f) is obtained from the matrix M_f provided by Peurifoy et al. (2006). For example, when clay in compacted measure is converted to loosen measure, the f is 1.41.

The index of maximum digging depth i and that of bucket size j are set to one (i.e., $i = 1$ *and* $j = 1$), respectively, in Step 10. After retrieving the maximum digging depth (H_M^i) of the i^{th} excavator from the equipment matrix $E_q(i,10)$, the method computes the optimum depth of cut (H_O^i), which is the depth of cut resulting in a full bucket in one pass, by multiplying H_M^i and E_L as shown in Eq.4.

$$H_O^i = E_L \times H_M^i \qquad (4)$$

The vector of optimum depth of cut (H_O) is appended to the last column of E_q (i.e., E_q=[E_q H_O]) in Step 12. The swing-depth factor (f_1^i) is computed by using A_S, H_O^i, and H_A defined in previous Steps. The cycle time (C_m) is determined by average value of entire cycle time (i.e., mean (E_t (:, 8) as shown in Eq.5.

$$C_m = mean\big(E_t(:,8)\big) \qquad (5)$$

The hourly production amount (P_i^j) of the i^{th} excavator (i.e., i=1: n) and j^{th} bucket size (i.e., j=1:m), which has (n×m) order, is computed enumerative for all available bucket j (i.e., j==m?) using the general output formula shown in Eq.6 (Peurifoy 2006). The method initializes the values of C_m, A_S, and R_P are obtained from the corresponding elements of E_F. The value of C_m is the historical cycle time which was performed by the same excavator and operator in a nearby excavating pit at the same job site. Where, P_i^j is hourly production in bank measure M^3, Q_j is the j^{th} bucket capacity in loose measure M^3, f is earth volume conversion factor, f_F is bucket fill factor, f_1^i is swing-depth factor of i^{th} excavator, f_2 is efficiency factor which represent the combining effect of job and management factors, t is operating time factor, and C$_m$ is the cycle time in seconds.

$$P_i^j = \frac{3{,}600 \times 0.76 \times Q_j \times \mathrm{f} \times f_F \times f_1^i \times f_2 \times t}{\mathrm{C_m}} \qquad (6)$$

The method checks if the series of Step 11-15 are computed for each and every excavator (i.e., i=1: n) and buckets (j=1:m) available under study (i.e., i==n?).

2.3 Identifying the Most Favorable Excavator Configuration

The method identifies the most favorable combination of maximum depth of cut (i), bucket size (j), and engine capacity (HP) which accomplishes the maximum hourly production. It is found by returning the inverse of function P_i^j (i.e., finverse(max(P_i^j))) as shown in Eq.7. The method retrieves the engine capacity (HP) of the excavator having E_{ID}.

$$[i, j, HP] = max(P_i^j)^{-1} \qquad (7)$$

2.4 Computing the Time, Cost, and Profit Performance

Given the optimal best-fit excavator configuration of the maximum digging depth (i), bucket size (j), and engine capacity (HP), the time, cost, and profit performance is computed as follows: In next step, the number of simulations (k) and the iteration counter (*iter*) are set to 120 and zero, respectively, assuming a 99% confidence level (Lee and Arditi 2006). Then, using the random variates of C_m generated by system, the hourly production amount (P) is computed by reusing Eq.7. The total job completion hours (T_T^{ij}) of the excavator having i^{th} maximum depth of cut and j^{th} bucket size is computed by dividing the total volume of work in bank measure (V_T) by the hourly production amount P_i^j as shown in Eq.8.

$$T_T^{ij} = \frac{V_T}{P_i^j} \qquad (8)$$

The working hours (H_L^{ij}) remained at the last working day and the volume of work to be performed at the last working day (V_L) are computed by calculating the remainder after division by using *rem* (T_T^{ij}, H_D) and by multiplying the P_i^j and H_L^{ij} as shown in Eqs.9 and 10, respectively. The H_D is the daily working hours (i.e., 8 hours/day) defined in Step 1.

$$H_L^{ij} = rem\big(T_T^{ij}, H_D\big) \qquad (9)$$

$$V_L = P_i^j \times H_L^{ij} \qquad (10)$$

With the working hours (H_L^{ij}) remained at the last working day, two options are available. The one (O_T=1) is to reduce the total job completion days by distributing H_L^{ij} to previous working days as night-work hours. When employing night shift, the quotient is computed by dividing T_T^{ij} by H_D (i.e., D^{ij} =*fix*(T_T^{ij}/H_D)) and no fuel saving strategy is used to expedite the job completion. Noteworthy is that reducing one working day (C_I) saves its corresponding indirect cost, but a percentage (α) of surcharge (e.g., α % of the excavator's hourly operating cost C_H) incurs. The other (O_T=2) is to perform the operation for the working hours H_L^{ij} which is the reminder at the right next working day after D^{ij}. In this case, an extra cost (C_E), which is a windfall profit (or easy money) to the equipment operator, occurs as shown in Eq.11.

$$C_E = \begin{cases} (\alpha + 1) \times C_H \times H_L^{ij} & if\ O_T = 1 \\ 0 & if\ O_T = 2 \end{cases} \quad (11)$$

Depending on the option selected, the total job completion cost (C_T^{ij}) of the excavator having i^{th} maximum depth of cut and j^{th} bucket size is computed either by multiplying the hourly owning and operating cost (C_H=C_F+C_V) and the rounded down value of T_T^{ij}/H_D (i.e., T_T^{ij}=*floor*(T_T^{ij}/H_D)) to the nearest integer and adding the extra cost (C_E, where O_T=1.) as shown in Eq.12 or by multiplying C_H and the rounded up value of T_T^{ij}/H_D (i.e., T_T^{ij} = ceil(T_T^{ij}/H_D)) to the nearest integer and adding the extra cost (C_E, where O_T=2.) as shown in Eq.13. Note that the value of T_T^{ij}/H_D is either rounded down or rounded up depending on whether the night shift is used or the equipment contract is based on day (not hour), respectively. The system checks which option is more favorable for maximizing the expected total profit by comparing $C_T^{ij}(1)$ and $C_T^{ij}(2)$ shown in Eqs.12 and 13, respectively.

$$C_T^{ij}(1) = floor\left(\frac{T_T^{ij}}{H_D}\right) \times \left(C_H^{ij} \times H_D + C_I\right) + C_E; O_T = 1 \quad (12)$$
$$C_T^{ij}(2) = ceil(T_T^{ij}/H_D) \times \left(C_H^{ij} \times H_D + C_I\right);\ O_T = 2 \quad (13)$$

The expected total profit (P_T^{ij}) of an excavator having i^{th} maximum depth of cut and j^{th} bucket size is computed by subtracting the total job completion cost (C_T^{ij}) from the contract amount commissioned as shown in Eq.14.

$$P_T^{ij} = C_u \times V_T - C_T^{ij} \quad (14)$$

2.5 Implementing Stochastic Time-Profit Tradeoff Analysis

The method computes the Eqs.8 to 14, for the maximum number of simulation (i.e., *iter*==*nSim?*) by iterating the simulation counter (i.e., *iter*=*iter*+*1*). After these iterations, the data cube of the hourly production, which maintains the values of *iter, i*, *j*, P_j, T_T^{ij}, C_T^{ij}, P_T^{ij}, $\tilde{\imath}$, and $\tilde{\jmath}$ in (n×m×*iter*) dimension, is generated in the stochastic mode and proceeds to Step 24. Noteworthy is that C_m is random variates generated. From this data cube, the most favorable set of maximum depth of cut ($\tilde{\imath}$) and bucket size ($\tilde{\jmath}$) that maximizes the expected total profit is identified by using the max function (i.e., max(P_T^{ij})), and the inverse of function P_T^{ij} shown in Eq.15. The method retrieves the engine capacity (HP) of the excavator having E_{ID} as well.

$$[\tilde{\imath}, \tilde{\jmath}, HP] = find(max(P_T^{ij})) \quad (15)$$

The probability to complete the job by a user-queried deadline T_U and a user-queried profit margin P_U are computed using the data cube, given an excavator of which configuration is the set of (i, j) or ($\tilde{\imath}, \tilde{\jmath}$). The normal distribution of T_T with mean (μ) and standard deviation (σ) is transformed to a standard normal distribution by changing variables to Z= (T_T- μ)/σ as shown in Eqs.16 and 17.

$$Pr(T_T \leq T_U) = \emptyset(\frac{T_U - \mu}{\sigma}) \quad (16)$$
$$Pr(P_T \leq P_U) = \emptyset(\frac{P_U - \mu}{\sigma}) \quad (17)$$

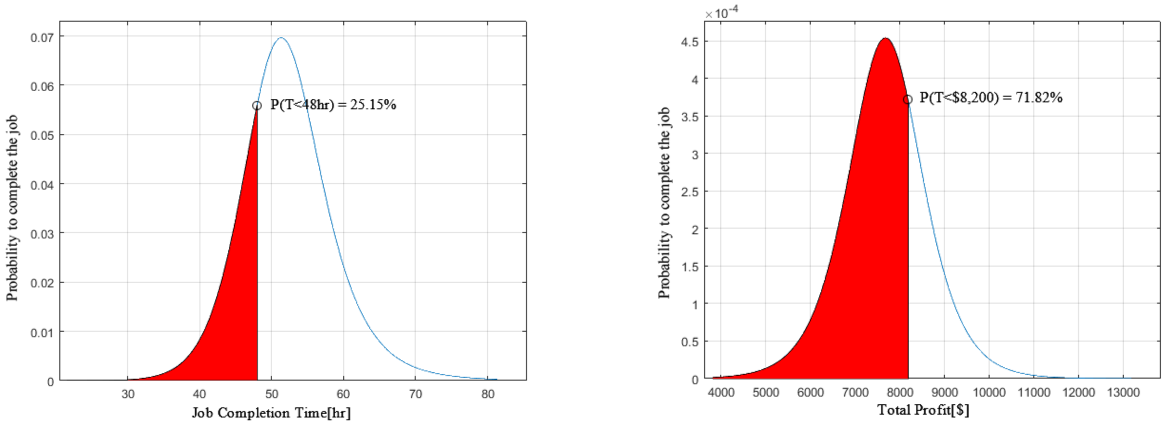
The system prompts an excavator which has the optimal configuration of maximum digging depth, bucket size, and HP with its T_T, C_T, and P_T. The stochastic mode defines the motions' times using their respective probability density functions (PDFs), computes the general output formula for a user-defined iteration, and compiles the sets of hourly productions and that of total profits. The historical data of each motion time, angle of swing, and rpm are processed to estimate their best-fit-PDFs and parameters.

III. Case Study

The earthwork of which the area, the average digging depth, the soil type, the job description, and the unit price of the job are 600m, 5ft, 'hard tough clay', 'placing the foundation of a large office building', and the owner's estimate of $1.0/bank measure M3. The hourly owning and operating costs (CH) of these backhoes are assumed to be equivalent to market rental costs even if it may not be true. They are maintained in a database. The equipment database administering hydraulic excavators having various range of bucket size (i.e., 2-10 CY) was implemented and used for a case study which was carried out for an earthwork contractor in Korea. The work package indicates the average depth of cut, the average angle of swing, job condition, management condition, the bucket fill factor, and the operating time are 3.0 ft, 120 degree, good, good, 75%, and 55 minutes/hour, respectively.

According to the contract information, the earthwork's control account parameters in matrix W_P is [1; 6; 8; 5; 'Hard tough clay'; 12,000] each of which denotes the unit price commissioned is $1/bank measure M^3; the target duration is 6 days; the working hours per day is 8; the average digging depth is 5 ft; the soil type is 'hard tough clay'; and the total volume of work is 12,000 bank measure M^3. Given the name of 'Back shovel' and the maximum digging depth of '22.1 ft', the method identifies the bucket fill factor (f_F) from matrix M_S (i.e., uniform (100, 110)) and retrieves the available excavators and their corresponding series of buckets from equipment database using Eq.3. Then, it gets the easiness to load the material of 30% which is corresponding value of the hard-to-load materials.

After computing the hourly production amounts for all excavators having different maximum digging depth, HP, and bucket size enumerative, the method, in deterministic mode, confirms that the optimal combination of maximum digging depth, HP, and bucket size are *19.4 ft, 168 HP, and 2.5*CY, respectively. In addition, the method computes that the maximum hourly production amount (P_i^j) of 310.533 bank measure m3/hr is achieved when the excavator having the optimal configuration is used. Given the maximum depth of cut of 19.4 ft and the bucket size of 2.5 CY, the total job completion hours (T_T^{ij}), the working hours (H_L^{ij}) remained at the last working day (H_L^{ij}), and the earth volume to be excavated at the last working day (V_L) were computed as 50.54 hours, 2.54 hours, and 788.75 bank measure m^3, respectively. Then, the method computes the set of the hourly production amount (P_i^j), and the expected total profit (P_T^{ij}) of each and every excavator which has many combinations of the maximum depth of cut (i), HP, and the bucket size (j), respectively. It appears that the biggest bucket out of the series is always the most favorable choice to each and every excavator.



(a) (b)

Figure 1. Job Completion Time(a) and Total Profit(b)

In stochastic mode, system identifies the most favorable combination of the maximum depth of cut ($\tilde{\imath}$) and its corresponding bucket size ($\tilde{\jmath}$) which results in the maximum expected total profit of \$ 7,610. Finally, it computes the probability of completing the job by a user-queried deadline of 48 hours or a user-queried profit margin of \$ 8,200 to 25.15% and 71.82% as shown in Figure 1, respectively. The probability distribution of the total job completion time and that of the total profit margin is negatively and positively skewed, respectively.

IV. Conclusion

This paper presents an easy-to-use computerized system that identifies the best-fit combination of the maximum digging depth, the engine size (HP), and the bucket size for eco-economic excavation, given an earthwork package, excavators' machine attributes, and operational constraints, etc. This study advances the body of knowledge relative to excavator selection, because it identifies the most favorable excavator configuration that minimizes the total excavating cost, and/or the fuel consumption before and during the excavating operation, hence, achieving the maximum total profit expeditiously. In addition, it provides the most favorable option and the right time when the fuel saving mode starts. Indeed, this tool allows collecting many input data expeditiously, implementing the deterministic and stochastic time-profit tradeoff analysis modes jointly and independently. The system allows earthwork managers to make more informed decisions with the exact global solution(s) found after searching the entire solution space enumerative and exhaustively. The comprehensive mathematical formulas relative to system contribute to expedite the excavating process by trading off the multi-objectives. It features the automatic configuration of excavator engine and its attachments and the automatic fuel saving mode initiation for smart excavating operation.

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