IN SEARCH OF THE IDEAL TRUCK-EXCAVATOR COMBINATION

*David Morley
Tim Joseph
Ming Lu
Department of Civil and Environmental Engineering
University of Alberta
116 St. and 85 Ave.
Edmonton, AB, Canada T6G 2R3
*(*Corresponding author: dmorley@ualberta.ca)*

IN SEARCH OF THE IDEAL TRUCK-EXCAVATOR COMBINATION

ABSTRACT

This paper considers the ideal truck-excavator combination, defined as the combination resulting in the lowest direct unit cost, in consideration of multiple haul scenarios characterized by different haul distances, material and equipment availability. Through the application of Monte Carlo simulation, selected for its unique ability to handle the uncertainty of activity durations, the "four to six passes" loading rule is shown to not correlate with the selection of the minimum cost fleet. Additionally, through the results of the simulation it is determined that the haul truck capacity has a greater effect on the overall efficiency of the system than does the excavator capacity. As a result, in order to arrive at efficient operations, the entire earthmoving system must be viewed as whole, namely, considering haulers together with excavators, as opposed to the popular method of first selecting a loading unit and then selecting a hauler obeying the "four to six passes" loading rule. Furthermore, truck utilization and excavator utilization exhibit an inverse relationship and neither directly correlates with the overall efficiency of the earthmoving operation. The following conclusions are drawn: first, with limited financial resources, it is more valuable to increase hauling unit size before increasing loading unit size and second, predefined rules or generalizations, not based on evidence, potentially eliminate optimal truck excavator combinations from being considered.

KEYWORDS

Earthmoving, fleet selection, heavy civil construction, mining, Monte Carlo simulation

INTRODUCTION

Current Practice

When browsing handbooks from equipment manufacturers or browsing classical textbooks, one is presented with the rule of thumb that for best results, considering output and economy, the hauling unit should be selected in order to be filled in "four to six passes" of the excavator (Peurifoy and Oberlender 2004). This approach neglects a critical factor in earthmoving operations; the hauling distance. Manufacturers' materials also generally neglect the effect that different materials may have on the loading capacity of the hauler and the excavator bucket. For example, when hauling a light material, such as muskeg (coversoil), haul trucks are restricted by the volume that can be contained in their box, whereas when hauling heavy secondary materials (subsoil), haul trucks are generally restricted by their payload capacity, and are loaded well below their volumetric capacity. The heaped bucket capacity of the excavator also varies depend on the material being loaded. By simply considering the implications of these two factors; material type and haul distance, one must question the realism of assigning a static ideal truck excavator combination.

Additional factors that are neglected with this approach are in relation to the indirect cost. When indirect costs are high, an emphasis is placed on achieving higher production in order to minimize the total cost per unit moved, however when indirect costs are low, there is less emphasis on the production rate and more emphasis on minimization of the direct cost as this correlates with a minimization of the total cost per unit moved. Also, larger excavators, while with larger buckets and higher lifting capacity than smaller machines, generally have slower hydraulics than the smaller machines. The larger lifting capacity is a benefit in heavy materials (secondary), but the slower swing speeds can be detrimental in excavation of lighter materials (muskeg).

The production efficiency of earthmoving operations is subject to complex interactions between the individual pieces of equipment that make up the earthmoving system. This further complicates the problem as due to the systemic nature of these operations, the system as a whole must be considered when estimating production or efficiency. In simplest form, this means that both the excavator and the haul truck must be considered. For more complex operations it may be necessary to consider other pieces such as dozers and compactors.

Much of the previous research determines the appropriate truck-excavator fleet applying the previously mentioned "four to six passes" rule. No justification is given concerning the validity of the rule, but rather is accepted as common knowledge. Additionally, much of the previous research, while useful in identifying which haul units should be considered based on performance characteristics and real-world applicability do not address the excavator-truck system as a whole. As a result, these approaches are useful for pre-selection of equipment units but do not provide a pathway to identifying the optimum truck excavator combination.

Previous Research

Karshenas (1989) selected the loading unit based on the production required and then selected the truck capacity for the selected loader determined by either: a rule of thumb of four to five passes to fill or direct unit cost. As shown later, this may effectively eliminate the optimal truck excavator combination from being selected.

Smith et al. (1995) used discrete-event simulation to analyze earth moving operations as a system, finding that the most important factors affecting production rate were in order: the number of trucks, haul return time, the number of passes per load and then the loading rate. This supports the previous statement that consideration of the number of passes per load is a poor indicator in determining the ideal truck-excavator combination. Additionally, Smith et al. (1995) showed that the factors affecting the production rate varied in their importance as haul distances varied. An explanation as to why the number of passes per load has remained prevalent in determining the optimum truck-excavator combination was given; the bucket passes per load is a factor controllable by the contractor. While this is true, it must be recognized that this factor is not deterministic and that there exist many other external factors that affect the reality of achieving it.

Lineberry (1995) identified that horsepower was the most important characteristic in selecting off-highway trucks in order to minimize the haulage cost. While horsepower is related to capacity, it was found to be a more accurate input variable allowing for a formula relating horsepower to haulage cost to be established. Experience and knowledge can be used to assure that the selected truck is not over-utilized or under-utilized in terms of power, but it was identified that further research would be required in order to link horsepower to operating conditions. While this formula considers ownership cost, overhaul cost, operating cost and mobilization, it must be noted that it minimizes the haulage cost of the haul unit only and does not minimize the haulage cost per unit at the system level as the loading unit is not considered. This approach is useful for pre-selection but does not guarantee an optimum truck and excavator combination.

Gransberg (1996) identified that the loading units' ability to load the haul units would determine the maximum productivity of the system and acknowledged that most approaches do not consider that the haul unit capacity, which is often not an even multiple of that of the loader bucket, and that a partial bucket takes approximately the same time to load as a full bucket. Considering these factors, Gransberg (1996) produced load growth curves for various loading facilities. A model was developed to determined the number of trucks required by dividing the truck cycle time by the truck loading time. The model remained deterministic and shared all limitations of deterministic models. Haul unit size was selected by looking at direct cost per ton relating to the loading unit only and did not consider the entire earthmoving system.

Genetic algorithms were applied by Marzouk and Moselhi (2002) in order to select the optimal loader-hauler fleet by minimizing the total costs, however the model must be provided with a fixed loader and truck types as inputs limiting its applicability to the industry.

Komljenovic et al. (2003) established a comparative coefficient for different mining trucks, and established that motor power depends strongly on gross vehicle weight, payload and heaped capacity. Their selection methodology considered only technical parameters and ratios and again was useful for narrowing the field of possibilities to be considered but did not guarantee an optimal pairing of hauler and loading unit.

Burt and Caccetta (2007) used a match factor previously applied to homogenous truck and loader fleets and applied it to heterogeneous truck and loader fleets. The match factor indicates whether the loader waits for the trucks (greater than 1) or the trucks wait for the loader (less than 1), or there is a perfect "match" of 1 where the trucks and loader are balanced. In reality this match does not exist due to queuing and cannot be determined by the deterministic inputs used to calculate the match factor. Additionally, cost was not accounted for and the authors clearly indicated that in practice, the match factor is not all that useful, as mining operations may want a lower match number in order to minimize cost, whereas construction operations may want a higher match number in order to maximize production.

Kirmanli and Ercelebi (2009) developed an expert system to select the excavator truck combination that minimizes production cost while satisfying the technical constraints. It must be noted, that with this approach, the excavator is selected before the haul units, in order to address production requirements. This implies that the number of haul units selected must be excessive in order to enable the excavator to be the limiting resource. The truck type is again based on being able to be filled within three to seven passes of the excavator. As did Karshenas (1989), Kirmanli and Ercelebi (2009), made the excavator the limiting resource in all cases. This approach may miss the true optimal truck excavator combination which minimizes unit cost.

Limsiri (2011) applied genetic algorithms, performing a similar operation to lower total equipment cost as Marzouk and Mosehli (2002), but allowed for a multiple truck and loader types to be considered and a heterogeneous fleet to be outputted. The solution space however remains limited to the initial considered options and cannot be easily applied in the field.

All of the previous approaches are limited by one or more of the following three aspects: 1) a deterministic model using average production rates is considered 2) only hauling units obeying the "four to six passes" rule are considered 3) it is assumed that the excavator must be the limiting resource. Any of the above assumptions can result in less than optimal truck excavator combinations, and can have serious repercussions when planning the overall length of the project.

METHODS

Methodology

Simulation is the only approach that can consider uncertainty in the duration of activity times when providing decision support for earthmoving operations, and thus, the results obtained from the process are deemed more indicative of the real world (El-Moslmani, Alkass and Al-Hussein 2002). Kannan (2011) clearly identified simulation as a valuable tool for earthmoving operations. As a result, Monte Carlo simulation was applied, in order to determine a realistic estimate for the number of loads dumped in a given shift, using the following as inputs: a specified number of trucks, truck type, material type, haul distance, excavator type and excavator and truck availability, defined as the probability that the specific machine is available to work. Simulation is limited however by the quality of its input. As a result, real world data for trucks' speeds and loading times obtained from the Caterpillar VIMS systems for a large Canadian contractor were analysed. Certain fleet configurations and material considerations were not available. Missing loading inputs distributions were determined from a similar recorded distribution by applying two multiplication factors, one for the effect of changing the amount of volume and one for the effect of changing the type of material. This is shown below:

$$\text{new distribution}=(\text{original distribution}) * (\text{volume factor}) * (\text{material factor}) \tag{1}$$

Where the volume factor is obtained by dividing the original truck volume by the new truck volume and the material factor accounts for the difference between the original swell factor and the new swell factor. It is important to note that the loading time distributions used do not recognize or reference the number of bucket passes required to fill the truck but rather are representative of the entire loading process of the truck selected.

Considerations and Parameters

All scenarios analysed considered 10 operating hours out of 12 calendar hours. All costs are in cost units, not dollars, in order to shield the confidential rates of the contractor; however, the cost ratio between equipment pieces remains constant. Two material types, three hauler types, four excavator types and two haul distances were considered. Specifications for the haulers can be found below:

Table 1- Hauler Specifications

		Capacity (bcm)		
Hauler Type	Tonnes	Coversoil	Subsoil	Cost/hr (unit/hr)
777	90.7	60.2	41.6	200
785	133	78	60.7	300
793	227	176	103.2	400

It is worth mentioning that all haulers are payload limited when hauling subsoil material due to its high density, and volume limited when hauling coversoil.

The excavator specifications can be found below along with the hauler size pairings suggested by the manufacturer:

Table 2- Excavator Specifications

Excavator Type	Heaped Capacity (m3)	Cost/hr (unit/hr)	Tonnes (hauler)
850	8	100	n/a
1200	8.25	250	38.0 to 59.0
1900	11.25	400	59.0 to 90.9
2500	15	500	90.9 to 168.0

The bucket fill factors for the two material types are as follows:

Table 3- Material Fill Factors

Material	Fill Factor
Coversoil	80%
Subsoil	95%

The theoretical number of bucket passes for each excavator to fill each hauler for both material types are shown below:

Table 4 - Number of Buckets Required to Fill Hauler with Subsoil Material

	Truck		
Excavator	777	785	793
850	5.5	8.0	13.6
1200	5.3	7.8	13.2
1900	3.9	5.7	9.7
2500	2.9	4.3	7.2

Table 5 - Number of Buckets Required to Fill Hauler with Coversoil

	Truck		
Excavator	777	785	793
850	9.4	12.2	27.5
1200	9.1	11.8	26.7
1900	6.7	8.7	19.6
2500	5.0	6.5	14.7

Haul distances considered were 5 km and 10 km. Excavator availability was considered to be 83% and truck availability was considered to be 90%. An analysis was performed to identify for each scenario, the excavator-truck combination that offered the lowest direct unit material cost. Indirect costs were not addressed as these are generally spread over the units of planned production. In other words, to lower indirect unit costs, one could use a) a larger machine capable of greater production or 2) multiple smaller machines. If the smaller machines offered a significant direct cost savings, this would generally be the better option as it not only reduces the cost of the operation but also provides a “cushion” to the earthmoving system against equipment breakdown. The daily cost of the equipment was calculated as follows:

$$\text{Daily Cost} = 12(C_{EX} + N_T C_T) \tag{2}$$

Where C_{EX} is the hourly cost of the excavator in cost units, N_T is the number of trucks in the fleet, and C_T is the hourly cost of the truck. The cost per bm^3 can then be calculated as:

$$\text{cost per bm}^3 = \frac{\text{Daily Cost}}{\text{Daily Output}} \tag{3}$$

Where the daily output is calculated as:

$$\text{Daily Output}\left(\text{bm}^3\right) = (\text{Truckloads/day})\left(\text{bm}^3 \text{ per truck}\right) \tag{4}$$

Custom Monte Carlo code was implemented in MATLAB, using the inputs above. The simulation was executed for a large quantity of runs for each scenario, as it was determined that 1000 runs was the minimum needed to assure that the outputs of the simulation would resemble normal distributions.

RESULTS AND DISCUSSION

The first case considered involved a 5 km coversoil haul where truck availability was set at 90% and excavator availability was set at 83%. The total cost is determined using Equation 2 and the cost per bm^3 was determined by applying Equation 3. The following lowest direct unit cost truck excavator combinations were identified:

Table 6 - Coversoil 5 km Haul (Truck Availability 90%, Excavator Availability 83%)

			Loads		Truck Utilization		Excavator Utilization			
Excavator	Truck	# of Trucks	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Daily Output (bcm)	Cost per bcm (unit/bcm)
850	777	4	83.5	2.9	84.0	2.7	52.5	2.1	5057	2.14
850	785	3	58.5	2.4	84.8	3.3	48.1	2.3	4524	2.65
850	793	2	32.5	2.0	80.5	4.7	60.8	3.9	5632	1.92
1200	777	6	124.8	3.7	81.5	2.3	62.4	2.3	7525	2.31
1200	785	4	76.5	2.8	82.3	2.9	62.2	2.4	6006	2.90
1200	793	2	32.8	2.0	81.0	4.8	60.7	4.0	5808	2.17
1900	777	5	96.0	3.5	78.6	2.6	67.3	2.9	5779	2.91
1900	785	4	70.4	3.0	78.9	3.2	69.6	3.1	5460	3.52
1900	793	3	52.6	2.7	77.4	3.7	70.1	3.7	9328	2.06
2500	777	9	186.9	5.2	78.3	2.2	70.9	2.6	11257	2.45
2500	785	6	121.7	3.7	81.7	2.3	61.0	2.67	9516	2.90
2500	793	3	55.3	2.9	77.6	3.6	62.4	4.2	9680	2.11

The simulation results indicate that the lowest direct cost for this haul can be achieved by using a 850 excavator paired with 793 haulers, a combination that entails 13.6 bucket-loading passes and would normally not be considered if the “four to six passes” rule had been applied. One could argue that this is an exception due to the abnormally large bucket size, for the machine weight class, of the 850, however, when observing the cost trend for the various haulers, the 793 hauler results in the lowest direct cost combination for all excavators, even though the “four to six passes” rule would exclude use of the 793 haulers for any coversoil operations. This is clearly shown in the figure below:

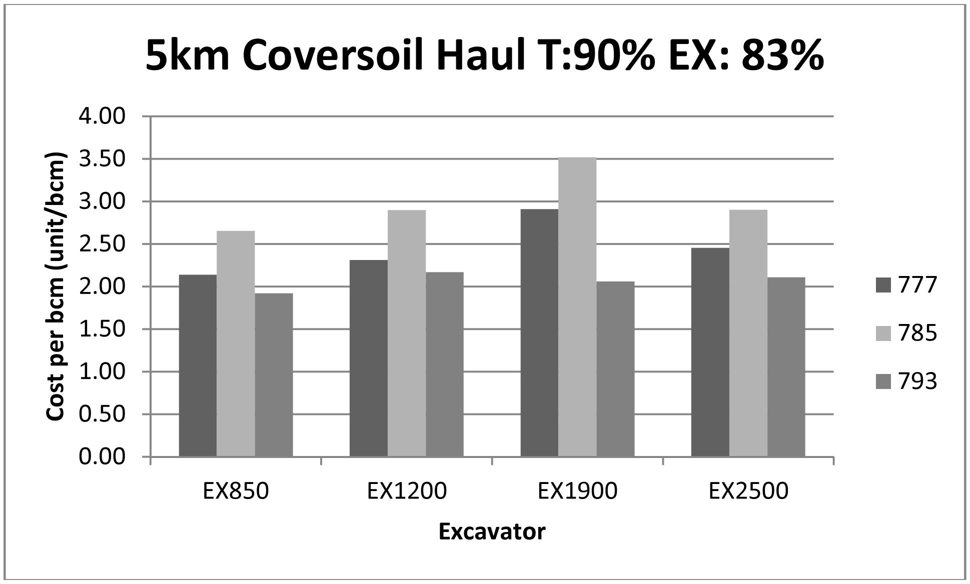

Figure 1- 5 km Coversoil Haul with 90% Truck Availability and 83% Excavator Availability

The next best combination is pairing any excavator with 777 trucks. This is in clear contradiction of the "four to six passes" rule as efficiency of the operation does not increase by using larger excavators which more readily match the rule.

The second case considered was a 10 km coversoil haul. Truck availability was set at 90% and excavator availability was set at 83%. The following lowest direct unit cost truck excavator combinations were identified:

Table 7 - Coversoil 10 km Haul (Truck Availability 90%, Excavator Availability 83%)

			Loads		Truck Utilization		Excavator Utilization			Cost per
Excavator	Truck	# of Trucks	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.	Volume (bcm)	bcm (unit/bcm)
850	777	6	71.6	2.5	87.1	2.7	45.7	2.1	4334	3.60
850	785	5	56.0	2.2	87.0	3.1	46.9	2.1	4368	4.40
850	793	2	21.7	1.4	86.3	5.2	41.3	2.9	3872	2.79
1200	777	9	107.0	3.1	85.9	2.4	54.2	2.4	6441	3.82
1200	785	6	66.8	2.3	85.4	2.8	55.1	2.2	5226	4.71
1200	793	3	31.3	1.8	82.6	4.4	58.8	2.6	5456	3.19
1900	777	8	89.7	3.0	82.6	2.6	63.7	3.0	5418	4.43
1900	785	6	63.3	2.4	82.9	3.0	63.7	2.7	4914	5.37
1900	793	4	44.7	2.3	82.4	3.9	60.5	3.2	7920	3.03
2500	777	14	166.9	4.0	84.0	1.9	64.4	2.6	10053	3.94
2500	785	11	123.8	3.6	83.6	2.3	63.1	2.9	9672	4.71
2500	793	5	55.6	2.7	79.8	3.5	63.8	4.3	9856	3.04

Once again, as with the 5 km coversoil haul, the lowest direct unit cost is provided by the 850 with 793 haulers. As with the 5 km coversoil muskeg haul as well, the figure below clearly shows that there is no efficiency gained by increasing the hauler size with excavator size and rather the lowest direct unit costs is obtained using a consistent hauler size across all excavators.

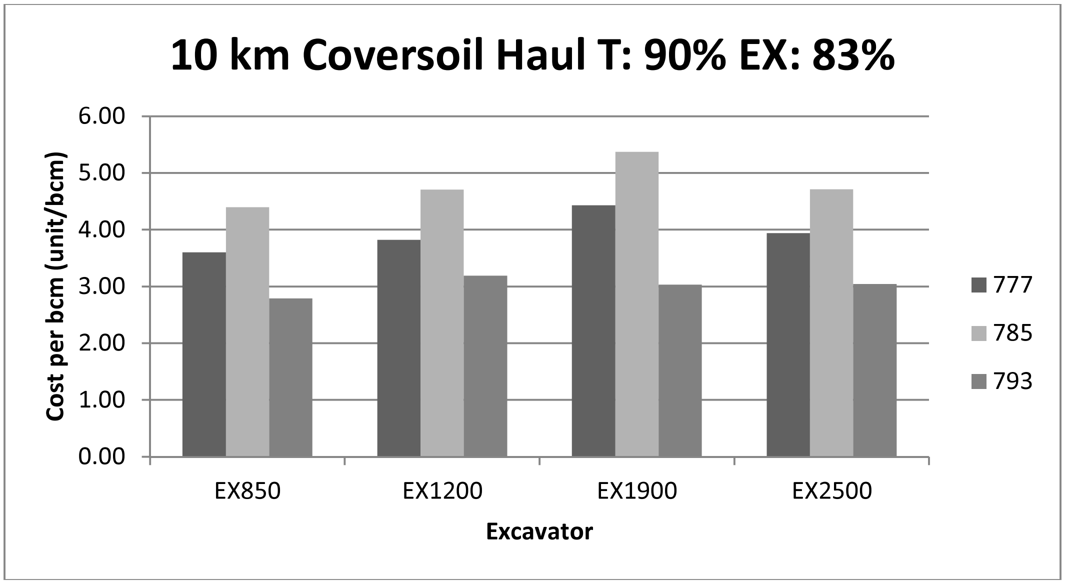

Figure 2 - 10 km Muskeg Haul with 90% Truck Availability and 83% Excavator Availability

The third case considered was a 5 km subsoil material haul. Truck availability was set at 90% and excavator availability was set at 83%. For this case, the lowest direct unit cost is provided by the 2500 excavator with 793 haulers. This combination is outside the range suggested by the "four to six passes" rule. Once again for other combinations, efficiency was not directly related to the size of hauler paired with the selected excavator.

The fourth case considered was a 10 km subsoil material haul. Truck availability was set at 90% and excavator availability was set at 83%. The lowest direct unit cost is, as with the 5 km haul, the lowest direct unit cost is provided by the 2500with 793 haulers. Other combinations follow a similar trend to the 5 km subsoil haul.

CONCLUSIONS

Through the four scenarios postulated, it can be concluded that the "four to six passes" rule does not hold when evaluating real world earthmoving system efficiency. Through the analysis of the simulation results, it is clear that small excavators can be paired with large haulers, requiring much more than six passes to fill, and result in lower direct unit cost than combinations suggested by the equipment manufacturers. In fact, nearly all the ideal combinations observed would have been classified as having excessive truck capacity in comparison to the manufacturer's suggestions. Furthermore, often the smallest excavator, paired with the largest hauler, resulted in the lowest direct cost for the light coversoil material. For the heavier secondary material the most efficient excavator combination for the 793 hauler is the 2500, however, one would have expected the 785 hauler paired with the 2500 to be a more efficient combination by applying the "four to six passes" rule.

In general, the "four to six passes" passes rule seriously underestimates the efficiency of using smaller excavators with larger trucks. This can be explained by multiple factors. First, the faster hydraulic speeds of the smaller excavators seem to easily overcome their bucket capacity limitations. Second, smaller excavators have much lower operating costs than their larger counterparts, and the cost increase, as capacity is increased, is not linear. From the data provided by the earthmoving contractor, it appears that an excavator that is twice as large will cost more than twice the cost of the smaller machine. Third, the actual loading time duration is a small portion of the total truck cycle time for a haul of any reasonable distance. As a result, decreasing the loading time by using a larger excavator only slightly raises the production, but greatly increases the operating cost, resulting in lower efficiency.

It is noted that material type has an enormous influence on the ideal truck excavator combination, and that haul distance has more of an effect on cost than the ideal truck excavator combination. The haul distance also does not have a linear effect on the ideal truck excavator combination. It is apparent that hauler size has a greater impact on efficiency and production of the earthmoving operations than the excavator size.

It is also noted that, selecting a loading unit first, to satisfy production requirements, and then selecting an appropriate hauler, results in a higher per unit cost than the optimal configuration. In no optimum scenario was the excavator observed to be the limiting resource as assumed in much of the previous research. As a result, average production rates are far from accurate in predicting production. It would be unreasonably expensive to provide enough haulers to ensure an excavator is kept occupied. As a result, the efficiency and the production must be observed from a system point of view. This is further supported by the fact that excavator utilization and truck utilization exhibit an inverse relationship. Due to queuing caused by the stochastic nature of the operations, both trucks and excavators cannot exhibit high utilization; one comes at the expense of the other.

In conclusion, there cannot be any pre-set rule to determining the ideal truck excavator combination. Rather, each case must be viewed and analyzed independently. However, certain trends can be observed. For one, undersized excavators, appear to offer more efficiency than the pairings suggested by the manufacturers. Smaller excavators offer numerous advantages in that they have much lower capital costs and can greatly increase the redundancy of the earthmoving operations compared to their larger counterparts. This is not to say that larger excavators do not have their place, as for certain conditions, they can offer greater efficiency than their smaller counterparts. For example, it may not be realistic to contain four smaller excavators in a small loading area in order to meet production, but rather, safer to use two larger excavators. Additionally, when labor is short, or associated operator costs are high, a larger machine offers more efficiency per worker. All things considered, with limited resources to be considered, it appears that a contractor would be better off spending money on acquiring large haul trucks before necessarily increasing their excavator sizes. There is no shortcut to detailed, thoughtful analyses, and predefined heuristic rules that are not supported by firm evidence may result in the abandonment of the true optimal solution.

REFERENCES

Burt, C.N. and Caccetta, L. (2007). “Match factor for heterogeneous truck and loader fleets.” Int. J. Mini. Reclamat. Environ., 21(4), 262-270.

Caterpillar Performance Handbook, 41st Ed. (2011). Caterpillar Inc., Peoria, Il.

El-Moslmani, K., Alkass, S. and Al-Hussein, M. (2002). “A computer module for multi-loaders-multi-trucks fleet selection for earthmoving projects.” Proc., Canadian Society for Civil Engineering Annual Conf., GE-107, Montreal, QC.

Gransberg, D.D. (1996). “Optimizing haul unit size and number based on loading facility characteristics.” J. Constr. Eng. Manage., 122(3), 248-253.

Kannan, G. (2011). “Field studies in construction equipment economics and productivity.” J. Constr. Eng. Manage., 137(10), 823-828

Karshenas, S. (1989). “Truck capacity selection for earthmoving.” J. Constr. Eng. Manage., 115, 212-227.

Kirmanli, C. and Ercelebi, S.G. (2009). “An expert system for hydraulic excavator and truck selection in surface mining.” J. S. Afr. Inst. Min. Metall., 109, 727-738.

Komljenovic, D., Fytas, K. and Paraszczak, J. (2003). “A selection methodology for rear dump mining trucks.” Proc. Of the fourth international conference on computer applications in the minerals industries, Calgary, Alberta, Canada

Limsiri, C. (2011). “Optimization of loader-hauler fleet selection.” Eur. J. Sci. Res., 56(2), 266-271.

Lineberry, G.T. (1985). “Optimizing off-highway truck characteristics for minimum haulage cost” Int. J. Mining Eng., 3, 295-310.

Marzouk, M. and Moselhi, O. (2002). “Bid preparation for earthmoving operations.” Can. J. Civ. Eng., 29, 517-532.

Peurifoy, R.L., and Oberlender, G.D. (2004). “Earthwork and Excavation”. Estimating Construction Costs, Fifth Edition, McGraw-Hill, New York, New York.

Smith, S.D., Osborne, J.R. and Forde, M.C. (1995). “Analysis of earth-moving systems using discrete-event simulation.” J. Constr. Eng. Manage., 121(4), 388-396.