University of Alberta

New Quantitative Methods for Planning Earthwork Operations

by

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Abstract

Earthwork operations are a critical component of major heavy civil projects, which often need to be successfully completed before other phases of construction operations can begin. As either stand alone or mining operations, they play a large role in Alberta's economy. If delayed, project schedules can often become irrecoverable and necessitate additional cost expenditures. Academic research has been performed; however, the industry has not significantly changed its "best practice" in over 100 years.

This research addresses the lack of adoption of previous academic developments and establishes the need for advancement in the face of inadequate current practice. Furthermore, new quantitative methods are proposed to simplify earthmoving simulation modeling and planning operations, including a) the use of an invariant input, the average weighted haul distance, and b) simulation derived formulas for accurate fleet selection. The methods were developed and validated through use of data provided by a major Canadian industrial earthworks contractor.

Preface

This thesis is organized in a paper format, consisting of, five main chapters and two appendices. Every chapter is an independent chapter and can stand alone, however all chapters relate logically and coherently to the thesis itself.

Chapter 1 provides an overview of the entire thesis and introduces background knowledge, problem statements, research objectives, and highlights the methodologies used and the resulting contributions. Chapter 2 reviews an old problem in the field: the ideal truck-excavator combination and clearly exposes the current industry practice is insufficient to provide a valid solution to the problem. Chapter 3 illustrates how for a fixed balanced grading site, the average weighted haul distance is invariant and can be used to simplify earthmoving simulation to aid in planning the site grading operations. Chapter 4 presents a new approach to utilizing simulation derived formulas in order to simplify Discrete Event Simulation implementation while allowing for an accurate fleet to be selected. Chapter 5 summarizes what has been done and offers a path forward.

Acknowledgement

I cannot hope to thank all of the people responsible for supporting and encouraging me to pursue this research. To my former and current colleagues in construction, my former teacher colleagues, my undergraduate and graduate professors, my classmates and my family, you have all played a part in allowing me to get to where I am today.

I need to thank my university advisor, Dr. M. Lu, who saw a unique background as an advantage allowed be to begin graduate research. I am grateful to have had his vision, guidance and encouragement throughout this process. Additional thanks go to Dr. S. M. AbouRizk, whose experience has been invaluable as a form of motivation and support.

Thanks needs to be given to my colleagues at Graham, who provided critical real world data, shared their experiences, listened to mine and who humored my visions.

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Chapter 1: Introduction

BACKGROUND

With the widespread availability of affordable personal computing in the 1980's, the application of discrete event simulation (DES) became increasingly popular in academia. A common application of this new tool was the classic earthmoving problem involving selecting the number of trucks and excavators for a given mass haul. Problem definitions varied from minimizing direct cost, minimizing total cost, minimizing duration, maximizing production, maximizing efficiency and various others. A large number of academic papers were published, with the goal of solving this seemingly simple problem. Other methods such as GA and expert systems were also employed.

In 2011, computer power was immensely more powerful and cheaper than in 1980. Surely, with such easily available resources, all earthmoving contractors must be using DES or other advanced computing methods to determine their fleet and plan their earthmoving operations.

Upon investigation into state-of-the-art practices of a select number of large Canadian heavy civil contractors, simulation was very rarely, if at all, applied.

Simulation

Simulation has been a popular tool for examining the earthwork problem and recent research has progressed beyond simulation modeling alone by optimizing the simulation outputs. Martinez (1998) used discrete event simulation to provide decision support for fleet selection. Harmelink and Bernal (1998) used simulation of haul durations to aid in linear scheduling. El-Moslmani et al (2002) developed a computer module employing DES for fleet selection considering multiple loaders and trucks for eathmoving projects. Marzouk and Moselhi (2002a and 2003b) employed SimEarth to aid in planning earthmoving operations and to evaluate different fleet scenarios. Zhang (2008) used multi-objective simulation optimization based on particle swarm optimization to select the equipment fleet. Alshibani and Moshelhi (2012) used GPS data to calculate the truck cycle time to aid in fleet selection.

Other Approaches

Smith (1999) used linear regression to estimate earthmoving productivity. Marzouk and Moselhi (2002b) used genetic algorithms involving quantitative and qualitative variables to determine near optimum fleet configurations. Ammar et al (2003) used a mixed integer programming model using deterministic variables to optimize earthwork allocation of a two dimensional problem. Marzouk and Moselhi (2003a) employed constraint-based GA to minimize the total cost of earthmoving operations. Marzouk and Moselhi (2004a) employed fuzzy clustering for estimating haulers travel time and combined GA with pareto optimality for multiobjective optimization of earthmoving operations (2004b). Schabowicz and Hola (2007) employed Artificial Neural Networks to predict the productivity of earthmoving systems. Moselhi and Alshibani (2009), combined GA and GIS technology to aid in decision support for heavy civil projects.

Previous research has been used either as decision support tool or for fleet optimization for known conditions. Due to the predominate micro architecture of these results, they have remained largely academic, as generally the information is either not available when fleet selection is preformed or the proposed methods and solutions cannot handle the real world deviations from the input data.

PROBLEM STATEMENT

The problem to be addressed in this research grows from the question of why simulation, which has been proposed by many researchers as the tool of choice to handle the issues faced by the heavy civil earthmoving contractor not being readily adopted in the field. The problem to be answered in this thesis is what to advance current simulation techniques by simplifying input modeling, a first step towards meta-modeling, and to allow easier adoption of this powerful technique by industry.

RESEARCH OBJECTIVES

The objectives of this research include, highlighting the continuing need for advanced quantitative methods in the field of heavy civil earthmoving operations, identifying factors allowing for simplification of current simulation methodologies to allow for easier adoption of by industry personnel, and to propose a path forward in development of future technologies relating to fleet planning in order to aid the industry.

This research focuses primarily on the early stage bidding process encountered often by industry professionals in their roles as estimators. At this stage the number of unknown unknowns, the things that someone isn't aware that they don't know, are numerous. As a result, in this research the terms ideal and optimum are used in terms of industry speak rather than their specific mathematical definition. For the purpose of this research the "ideal" solution is the theoretical perfect solution that in fact, is not possible to obtain in reality. The "optimum" solution is not the mathematical global optimum but rather, the best decision/choice that can be made given the input data available at the time when the decision is being made in order to provide a realistic, achievable solution moving forward which attempts to maximize potential upside while minimizing the downside or risk.

METHODOLOGIES

The methodologies applied to answer the research objectives include the following:

Comprehensive review of domain literature

The most serious shortfall of previous research is not a flaw in any one approach, or a lack of academic vigor, but a lack of attention to a critical aspect of the industry. The industry, especially the heavy civil industrial sector, moves at a pace that performances cannot be easily benchmarked. Staff turnover is high, and projects arise and die in minutes. To be able to keep up with this chaotic nature, decision support tools have to be able, to be utilized by a large number of managerial staff, not simply simulation experts. Entry level engineers should be able to apply the tools.

Identifying reasons for resistance to embracement of previous research through conversation with domain experts

A new approach is needed that presents transparent solutions in order to allow different industry members to apply their own prejudices in solving the problem. Decision support must be able to be applied in a comparable time window during which a seasoned industry professional examines gut feelings and consults experiences.

Simulation

Simulation provides the ideal platform for dealing with the uncertainty that must be recognized when addressing industry problems. It also provides quantitative classification and identification of risk.

Mathematical methods

The heavy civil earthmoving industry has long utilized heuristic rules in order to plan operations. The rules need to be confirmed and/or rejected by quantitative analysis before being applied.

ACADEMIC CONTRIBUTIONS

The facts presented in this thesis research will contribute to the continual need for advancement of simulation methods and modeling in an attempt to address the true nature of the industry, while preserving its place as the de facto tool of choice to solve these problems. Additionally, the identification of the average weighted haul distance as invariant, will simplify modeling moving forward and is a preliminary step on the path towards meta-modeling, which will serve to guide and inspire future research. Furthermore, the presentation of quantitative linear formulas derived from simulation, opens the door towards continuing research in this area so as to tackle the difficulties generally associated with simulation, specifically, the time requirements.

INDUSTRY CONTRIBUTIONS

The research clearly identifies to industry that current practice is not sufficient and that development and searching for other alternatives is a necessity. Methods have been proposed to reduce the burden of simulation implementation by simplifying a) the input data and b) the time and expertise required to obtain meaningful conclusions.

CONCLUSIONS

The research confirms that although simulation is not readily applied in the field, it is of critical importance and validates the work proposed and done by previous researchers. Based on the concerns of industry personnel in relation to the implementation of simulation in their day to day activities, a key factor to simplify input modeling was identified. Additionally, a new method using quantitative formulas is proposed allowing for reducing cost, both in time and expertise, and additional repeatability in drawing meaningful conclusions relating to the optimum fleet configuration.

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Chapter 2: In Search of the Ideal Truck-Excavator Combination[1]

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 and depends 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.

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[1] A version of this chapter has been submitted for publication. 30th International Symposium of Automation and Robotics in Construction and Mining (ISARC 2013) Proceedings, ISBN: 978-1-926872-16-2

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 determine 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:

$$\text{new distribution} = (\text{original distribution}) * (\text{volume factor}) * (\text{material factor}) \qquad \text{Eq. 2-1}$$

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 analyzed 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 2-1: 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 2-2: 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 2-3: 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 2-4: Number of Buckets Req.to Fill Hauler with Subsoil

	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 2-5: 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 1) 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:

$$\text{Daily Cost} = 12(C_{EX} + N_T C_T) \qquad \text{Eq. 2-2}$$

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 bm3 can then be calculated as:

$$\text{cost per bm}^3 = \frac{\text{Daily Cost}}{\text{Daily Output}} \qquad \text{Eq. 2-3}$$

Where the daily output is calculated as:

$$\text{Daily Output }(\text{bm}^3) = (\text{Truckloads/day})(\text{bm}^3\text{ per truck}) \qquad \text{Eq. 2-4}$$

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 2-2 and the cost per bm3 was determined by applying Equation 2-3. The following lowest direct unit cost truck excavator combinations were identified:

Table 2-6: Coversoil 5 km Haul (Truck Availability 90%, Excavator Availability 83%)

Ex.	Truck	# of Trucks	Loads Mean	Loads St. Dev.	Truck Utilization Mean	Truck Utilization St. Dev.	Excavator Utilization Mean	Excavator Utilization 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	2.7	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:

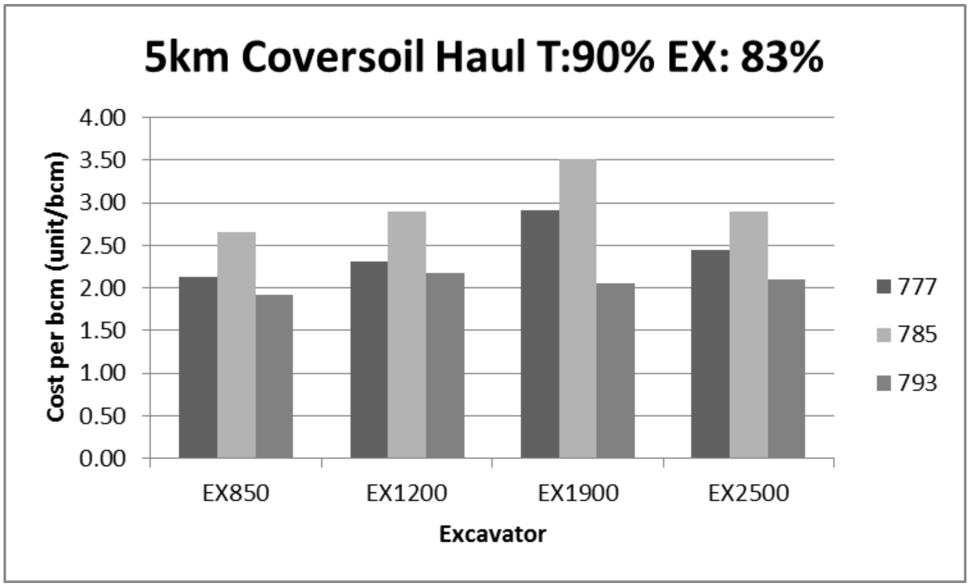

Figure 2-1: 5 km Coversoil Haul with 90% Truck Availability and 83% Excavator Availability

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 2-7: Coversoil 10 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.	Volume (bcm)	Cost per 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.

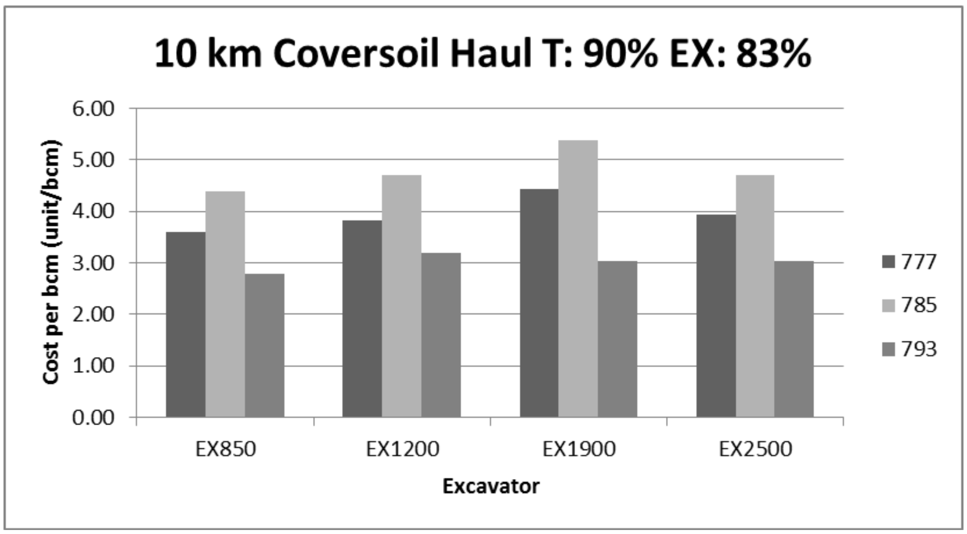

Figure 2-2: 10 km Muskeg Haul with 90% Truck Availability and 83% Excavator Availability

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.

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Chapter 3: Identification of the Invariant Average Weighted Haul Distance to Simplify Earthmoving Simulation Modeling in Planning Site Grading Operations[1]

INTRODUCTION

Throughout the years, numerous different methodologies have been applied to provide decision support to earthmoving operations. Queuing theory (Touran and Taher 1998), expert systems (Christian and Xie 1996), deterministic models based on real world data (Gransberg 1996), neural networks (Shi 1999; Schabowicz and Hola 2007), linear regression (Smith 1999), experience databases (Kannan and Vorster 2000), single objective optimization using genetic algorithms (Marzouk and Moselhi 2002a; Tam et al. 2007; Limsiri 2011), single objective optimization using constraint-based genetic algorithms (Marzouk and Moselhi 2003a), multi-objective optimization (Marzouk and Moselhi 2004a), fuzzy logic (Marzouk and Moselhi 2004b), spreadsheet applications (Eldin and Mayfield 2005), multiple regression (Han et al. 2008), particle swarm optimization (Zhang 2008), combined genetic algorithm and linear programming optimization (Moselhi and Alshibani 2009), efficient frontier analysis (Alshibani and Moselhi 2012), match factor (Burt and Caccetta 2007), heuristic methods (Karshenas 1989), expert systems (Kirmanli and Ercelebi 2009) and simulation (Shi and AbouRizk 1994; Smith et al. 1995; Hajjar and AbouRizk 1997; Martinez

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1998; Shi and AbouRizk 1998; Marzouk and Moselhi 2002b; Marzouk and Moselhi 2003b; Marzouk and Moselhi 2004a, Cheng et al. 2011, Alshibani and Moselhi 2012) have all been applied to the earthmoving problem.

In reality, heuristics still provide the predominant decision support to practitioners working in the complicated, fast-moving construction field. Heuristics are often given in the form of rules generalized from the common wisdom of domain experts, lending straightforward, experience-based decision support. For example, 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).

Discrete-event simulation is a powerful method to imitate the behavior of a real-world system over time by modeling repetitive processes in which durations of operations are stochastic and many resources interact (Law and Kelton 2000). Simulation keeps track of the changes of the state of a system occurring at discrete points of time and builds a logical model of a system for experimenting on a computer (Pritsker 1986). The statistical data generated from the experiments provide modelers with insight into system's resource application, interactions, and constraints. The simulation methodology of activity cycle diagrams (ACD) lends itself well to modeling construction operations. ACD-based construction simulation tools have evolved from the original CYCLONE methodology (Halpin 1977) to the programmable STROBOSCOPE

(Martinez 1996). However, the use of simulation in construction practices has generally been random and sporadic, and numerous attempts to interest major construction companies in simulation as a productivity-enhancing means have proved unsuccessful (Halpin 1998).

When reviewing past research, the popularity, success, and longevity of using simulation to aid in the decision support process for earthmoving operations is obvious. This can be attributed to the fact that all other methods fail to consider uncertainty in the duration of activity times, and thus, results obtained through use of simulation have the most credibility in the real world (El-Moslmani, Alkass and Al-Hussein 2002). As a result, simulation is clearly identified as a valuable tool for analyzing repeated activities often experienced in earthmoving operations (Kannan 2011).

Simulation, however, can be limited by the fact that the output of the program depends on the quality of the input (Kannan et al. 2000). Most simulation programs use distributions of activity times taken from historical databases, which may not be reasonable to use when facing new scenarios. Recent advances in GPS-based equipment tracking technology have allowed for near real time inputs to be constructed (Alshibani and Moselhi 2012), but this does not aid in extrapolating the simulation model to other projects. As most simulation models for construction are only used once or twice, most simulation programs focus on breadth of application rather than depth (Kannan et al. 2000). This can be attributed to a lack of resources, both in time and expertise, in the construction industry, and as a result, detailed macro-level simulation (system level) models and certainly micro-level (individual entity) simulation models are not often developed. Simple generic models may be developed and used for multiple projects; however, they do not achieve the accuracy of their simulation counterparts. In order to be able to apply the advances in simulation optimization developed in the academic world to the earthmoving industry, improvements are needed to simplify the resource demands, both in time and expertise, of current simulation practices, while maintaining accuracy. Kannan et al. (2000) defined meta-level simulation as "the modeling of domain specific requirements through rules." By establishing rules, equivalently, joining inputs and outputs of the simulation such as the load time and final payload, as in Kannan et al. (1999), portions of the macro-level simulation may not be required to be constructed in great detail, or can be omitted altogether, offering the possibility of simplification of the input modeling required.

Given the complexities and constant changes in field operations, we identify one major bottleneck to adopting simulation modeling in the heavy and civil construction field: it is rare to find personnel in this industry who possess both the simulation knowledge and the field experience required and who also have sufficient time to implement simulation modeling as effective decision support in the limited time period available for estimating and planning earthmoving operations. This accounts for our observation that simulation is much desired but not often applied in the field.

This paper presents a new meta-level rule to aid in simulating earthmoving operations. It is clearly shown that the average weighted haul distance can be used as a critical input to build a simplified simulation model to substitute for a detailed simulation model which considers specific earth movement patterns, while still producing outputs of comparable accuracy. This allows the benefits of simulation to be achieved without incurring the long modeling time and high application cost commonly associated with developing a detailed simulation model. Meanwhile, GPS technologies are certainly valuable tools for data collection in earthmoving operations, however, this paper focuses on the planning and estimation stages of an earthmoving project. Current practice generally collects original ground elevation data used for site grading design by resorting to real time kinematics (RTK) GPS survey technology. This technology provides point coordinates on a site grid layout as input data for ensuing design and construction analysis. The proposed new approach is intended to augment the GPS survey technology with integrated analysis of site design and method design, lending relevant decision support to construction engineers in constructability analysis and determination of fleet selection, project execution planning, project duration or project cost.

METHODS

Definition of Haul Effort:

The time duration and resource requirements for earthwork operations depend primarily on two factors, namely: the volume of material that needs to be moved and the distance that the specific volume needs to be moved. The types of resources, scrapers vs. trucks for example, should be determined to be commensurate with the volume and the haul distance while also considering factors such as road conditions, equipment conditions and equipment capabilities. The two factors, haul distance and volume, can be combined to create a single factor: haul effort (Son, Mattila and Myers 2005), which is commonly expressed in ton-kilometers, but is here defined as the volume moved multiplied by the distance over which the volume is moved:

$$H_{effort} = \sum_{i=1}^{m} \sum_{j=1}^{n} V_{ij} D_{ij} \qquad \text{Eq. 3-1}$$

Where H_{effort} is the total haul effort (m^4), V_{ij} is the volume moved between the *i*-th and *j*-th cell (m^3) and D_{ij} is the distance between the *i*-th and *j*-th cell (m). Current industry practice is to ensure that, if possible, the volume moved on site is balanced, given a proposed ground surface and the existing stripped ground surface, where the sum of the total cut volume is equal to the sum of the total fill volume, in order to avoid the cost associated with importing or exporting material. For the specific proposed ground surface overlaid against the specific existing stripped ground surface, the total volume to be moved on a balanced site is expressed as Equation 3-2:

$$V = \sum_{k=1}^{q} C_k = \sum_{l=1}^{p} F_l \qquad \text{Eq. 3-2}$$

Where V is the total volume to be moved (bm^3), C_k is the cut volume in cell *k* (bm^3) and F_l is the fill volume in cell *l* (bm^3). This allows the average weighted haul distance to be calculated as:

$$\overline{D} = \frac{H_{effort}}{V} = \frac{\sum_{i=1}^{m}\sum_{j=1}^{m} V_{ij} D_{ij}}{V} \quad \text{Eq. 3-3}$$

And can be expressed as:

$$\overline{D} = \frac{1}{V}\sum_{\alpha=1}^{mn} V_{\alpha} D_{\alpha} \quad \text{Eq. 3-4}$$

Where $\overline{D}$ is the average weighted haul distance (m). Haul effort has been long applied by construction practitioners when analyzing operations in linear earthworks, such as road construction (Peurifoy and Oberlender 2004). On such linear earthwork operations, the mass-haul diagram shown below can be readily applied to determine the total cut and fill volumes, the amount of earth moved and the average haul distance over which a certain amount of specific material travels.

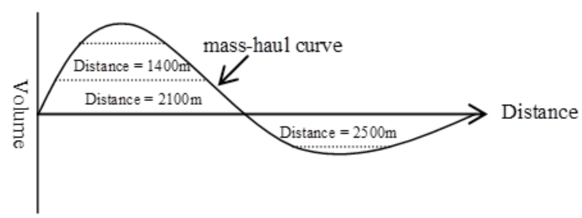

Fig. 3-1: Mass-haul diagram

Comparison to the Center of Mass:

For a system of particles, each with mass m_i and position r_i, the coordinates R of the center of mass can be fixed by the following formula:

$$R = \frac{1}{M}\sum_{i=1}^{n} m_i r_i \quad \text{Eq. 3-5}$$

M in Equation 3-5 is the sum of the masses of all the particles. This equation has the exact form of the previous equation, Eq. 3-4., which defines the average weighted haul distance, $\overline{D}$. For a rigid body, the center of mass is fixed (Taylor 2005), thus, R is constant, and therefore, for a fixed, balanced site grading plan, it can be inferred that $\overline{D}$ can be approximated as constant as well. Given a fixed, balanced site, the original ground elevation is known and the proposed design elevation has been set, thus the specific cut/fill areas and a fixed mass distribution can be calculated, which results in the zero net import/export of material. Note the common practice in the industry to minimize importation/exportation of material as the cost of over-the-road trucking of material can add a significant part to the total project cost. This inference is further corroborated through conducting simulation experiments on a testing case, which is shown and discussed in ensuing sections. Therefore, application of a heuristic approach which calculates only one specific material movement pattern is justified, because regardless of the selected starting point or particular cut-to-fill movement patterns among individual cells, the returned average weighted haul distance remains constant.

A Heuristic Algorithm for Determining the Haul Effort:

An earthwork contractor calls for a systematic, structured, and practical approach to plan and grade a site instead of randomly jumping from one cell to another in the site grid. To address this concern and to produce a reasonable material movement plan, a heuristic algorithm, inspired by the popular computer game "Minesweeper," is first proposed and implemented in later simulation experiments on a test case. The algorithm applies a greedy approach to choose the most appropriate fill cell destination for the material excavated from a current cut cell as per the balanced site grading design.

The algorithm takes as input a volume matrix created from a proposed elevation matrix (P) and an existing elevation matrix (E) calculated by the following Equation 3-6 given in Yi and Chelberg (1993):

$$V_{(i,j)} = \frac{G^2}{4}\left[\left(E_{(i,j)} + E_{(i+1,j)} + E_{(i,j+1)} + E_{(i+1,j+1)}\right) - \left(P_{(i,j)} + P_{(i+1,j)} + P_{(i,j+1)} + P_{(i+1,j+1)}\right)\right] \quad \text{Eq. 3-6}$$

Where $V_{(i,j)}$ is the volume (m^3) between P and E for cell (i,j). G is the size of the grid spacing (m), $E_{(i,j)}$ is the existing ground surface elevation at point (i,j), and $P_{(i,j)}$ is the proposed ground surface elevation at point (i,j). The algorithm selects a specified starting point, begins with searching the closest fill cell and then identifies the closest available cut cell(s) in relation to the given fill cell. The distance between a fill cell and a cut cell is calculated as follows:

$$D = G\sqrt{\left(x_f - x_c\right)^2 + \left(y_f - y_c\right)^2} \quad \text{Eq. 3-7}$$

Where G is the size of the grid spacing (m), x_f is the x-coordinate of the fill cell, x_c is the x-coordinate of the cut cell, y_f is the y-coordinate of the fill cell and y_c is the y-coordinate of the cut cell. This is the approach used in this paper; however, where traveling directly across the cell on site is not permissible, the distance between a fill cell and a cut cell can also be calculated as the travel distance in both directions as in Equation 3-8, which is longer than the diagonal distance.

$$D = G\left(\left(x_f - x_c\right) + \left(y_f - y_c\right)\right) \quad \text{Eq. 3-8}$$

Note the formula can also be refined to calculate the distance from the fill cell to the cut cell, when the hauling path must pass through certain coordinates or even considering the grade and rolling resistance in the site space. If multiple cut cells are equidistant from the fill cell, the algorithm selects the cut cell with the least number of conflicts. Primary conflicts are defined as the number of fill cells located directly beside the cut cell, and secondary conflicts are defined as the number of fill cells located directly diagonal to the cut cell. If the volume of the cut cell is larger than the volume required by the fill cell, the volume of the fill cell is updated to be zero and the volume of the cut cell is updated to be the original volume minus the volume moved to the fill cell. A new fill cell is then chosen, moving in a user-specified direction. If the volume of the cut cell is smaller than the volume required by the fill cell, the volume of the cut cell is updated to be zero and the volume of the fill cell is updated to be the original volume minus the volume moved into the cell. The next best cut cell is then chosen to be used to fill the cell, and the process repeats. At every step, the haul effort for that movement is calculated and added to the total haul effort. A flowchart is shown below:

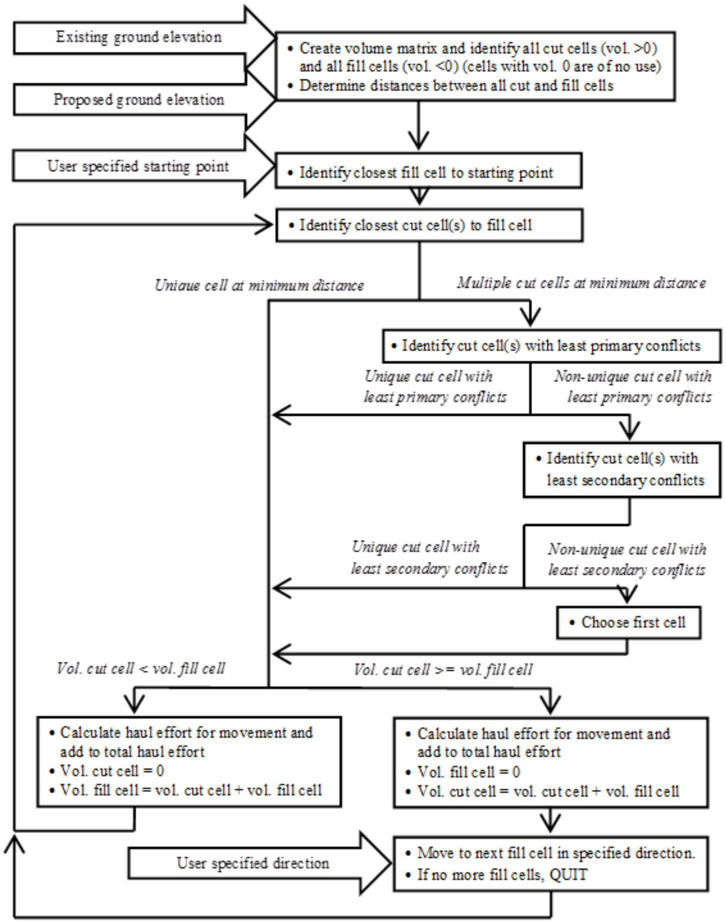

Figure 3-2: Heuristic algorithm flowchart

RESULTS AND DISCUSSION

Verification by Use of a Test Case:

To illustrate and verify the relative stability of the average haul distance and the simplified simulation modeling method being proposed, a 700 m by 600 m test case was chosen. The existing ground elevation matrix is shown in Figure 3-3. Grid spacing is 100 m by 100 m.

Existing ground elevation (m)							
	x						
y	102.76	102.22	102.10	102.09	101.45	101.10	100.92
	103.78	103.38	102.99	102.99	102.42	101.86	101.96
	104.57	104.51	104.25	103.68	103.02	102.62	102.42
	105.37	105.57	105.20	104.86	103.92	103.39	102.95
	106.28	106.36	105.78	104.87	104.16	103.41	103.14
	106.87	106.60	106.09	105.42	104.45	103.89	103.17

Figure 3-3: Existing ground elevation matrix

Additionally, the following proposed site elevation matrix is also determined, as the cut and fill volumes to be moved on site are already balanced.

Proposed site elevation (m)							
	x						
y	104.78	102.79	100.79	98.80	96.80	94.81	92.81
	106.78	104.78	102.79	100.79	98.80	96.80	94.81
	108.77	106.78	104.78	102.79	100.79	98.80	96.81
	110.77	108.77	106.78	104.78	102.79	100.80	98.80
	112.76	110.77	108.77	106.78	104.79	102.79	100.80
	114.76	112.76	110.77	108.78	106.78	104.79	102.79

Figure 3-4: Proposed ground elevation matrix

Using Equation 3-6, the following volume matrix is constructed. It is noteworthy that the calculated fill volumes were originally calculated in compacted cubic meters, but then updated as bank cubic meters (bm^3) by applying a shrinkage percentage of 5% in Eq. 3-9 (Peurifoy and Oberlender 2004):

$$B = \frac{C}{\left(1 - \frac{S}{100}\right)} \qquad \text{Eq. 3-9}$$

Where S is the percentage of shrinkage, B is the volume of undisturbed soil (bm^3) and C is the volume of compacted soil (cm^3).

Volume per cell (bm^3)						
	x					
y	-18389	-1209	17496	34392	49037	66508
	-28604	-10530	6891	22337	36807	54103
	-39662	-19956	-3013	10807	24428	40448
	-51298	-32066	-16860	-3496	9298	24269
	-65645	-48018	-34049	-21633	-8506	6114

Figure 3-5: Site volume matrix

The previously described heuristic algorithm was then executed and the following results returned. In Table 3-1, the column "Cut" indicates the x, y, location where the material is taken from, and the column "Fill" indicates the x, y, location where the material is placed.

Table 3-1: Detailed material movements

Cut		Fill		Volume	Distance	Effort
x	y	x	y	(bm^3)	(m)	(bm^4)
3	1	1	1	17496	200	3499286
3	2	1	1	893	224	199636
3	2	1	2	5999	200	1199794
4	2	1	2	22337	300	6701211
4	1	1	2	268	316	84850
4	3	1	3	10808	300	3242310
4	1	1	3	28855	361	10403638
5	4	1	4	9299	400	3719456
5	3	1	4	24428	412	10072046
4	1	1	4	5269	424	2235536
5	2	1	4	12303	447	5501863
5	2	1	5	24505	500	12252710
6	5	1	5	6115	500	3057285
6	4	1	5	24269	510	12374933
6	3	1	5	10756	539	5792536
5	1	2	1	1210	300	362895
5	1	2	2	10530	316	3329989
5	1	2	3	19956	361	7195350
6	3	2	4	29692	412	12242503
5	1	2	4	2374	424	1007224
5	1	2	5	14967	500	7483635
6	2	2	5	33051	500	16525745
6	2	3	3	3014	316	952975
6	2	3	4	16861	361	6079172
6	2	3	5	1178	424	499745
6	1	3	5	32872	500	16435900
6	1	4	4	3497	361	1260789
6	1	4	5	21633	447	9674701
6	1	5	5	8506	412	3507250

The total volume to be moved is 402,942 bm^3, and the total haul effort calculated is 166,894,964 bm^4. The average weighted haul distance can then be determined as:

$$\begin{aligned}\overline{D} &= \frac{H_{effort}}{V} \\ &= \frac{\left(166{,}894{,}964\ \mathrm{bm}^4\right)}{\left(402{,}942\ \mathrm{bm}^3\right)} \\ &= 414\ \mathrm{m}\end{aligned} \qquad \text{Eq. 3-10}$$

In site grading practice, the grid width is generally set to sufficiently represent the complexity of the existing ground profile and the site grading design. In the case study, the site can be sufficiently profiled by using 100 m grid width; in each 100 m×100 m grid, the earth material to be handled is assumed to concentrate on the center of the grid in order to simplify the estimation of the haul distance between two relevant grids. In contrast with the center of mass analysis, it is not practical to apply indefinitely small grids to map out the site area and determine the haul effort by integrating the earthworks. Thus, marginal variation on the resulting average haul distance reflecting the grid precision is unavoidable. To shed light on the relative stability of the average haul distance, we divide each 100 m×100 m cell into four 50 m×50 m sub-cells. The volume of earth to be processed in each 100 m×100 m cell is also equally distributed in four sub-cells. The earthmoving operations still follow the identical cut-fill cell combinations as previously determined for the current case using the 100 m grid width. Note, haul distances are determined by connecting the centers of two sub-cells involved. The total volume of earth processed remains 402941 bm^3. The total haul effort is determined as 165,805,946 bm^4, resulting in the weighted average haul distance of 411.5m. Compared with the result obtained in the same case applying 100 m grid width, which is 413 m, a difference of 1.5 m (or 0.36%) is observed in the average haul distance. This marginal difference can be attributed to the use of different travel distance values between cut and fill cells as a result of subdividing the cells. The detailed haul distance and volume data along with haul effort calculation are given in Appendix A.

Variation of Average Haul Distance

In order to further corroborate our analogy relating the average weighted haul distance to the unchanging center of mass, custom Monte-Carlo simulation code was written in MATLAB. Note in order to draw generic conclusions, the heuristic algorithm described in the previous section is not applied to determine the earthmoving patterns between cut and fill cells. Instead, the simulation program randomly chooses cut cells and fill cells, and determines the haul effort of each material movement. A flowchart is presented below:

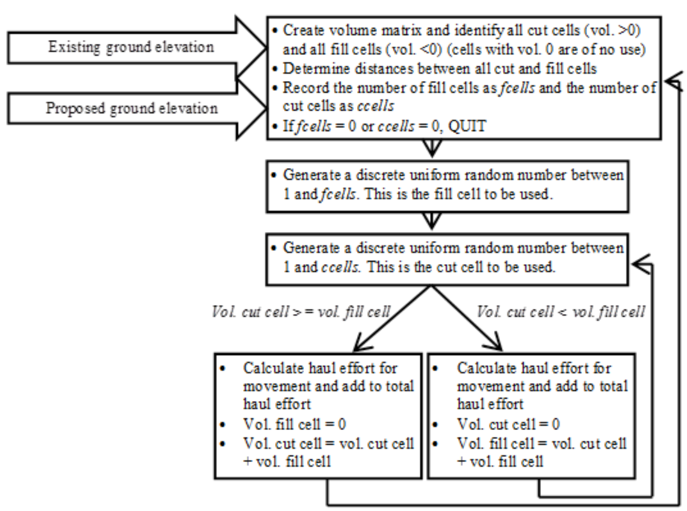

Figure 3-6: Simulation of material movement flowchart

The simulation was run for 100 runs and the following results returned:

Table 3-2: Simulated material movement results

Simulation outputs	Mean	Max	Min
Total haul effort (bm4)	173,790,409	181,231,133	166,742,664
Weighted average haul distance (m)	431	450	413

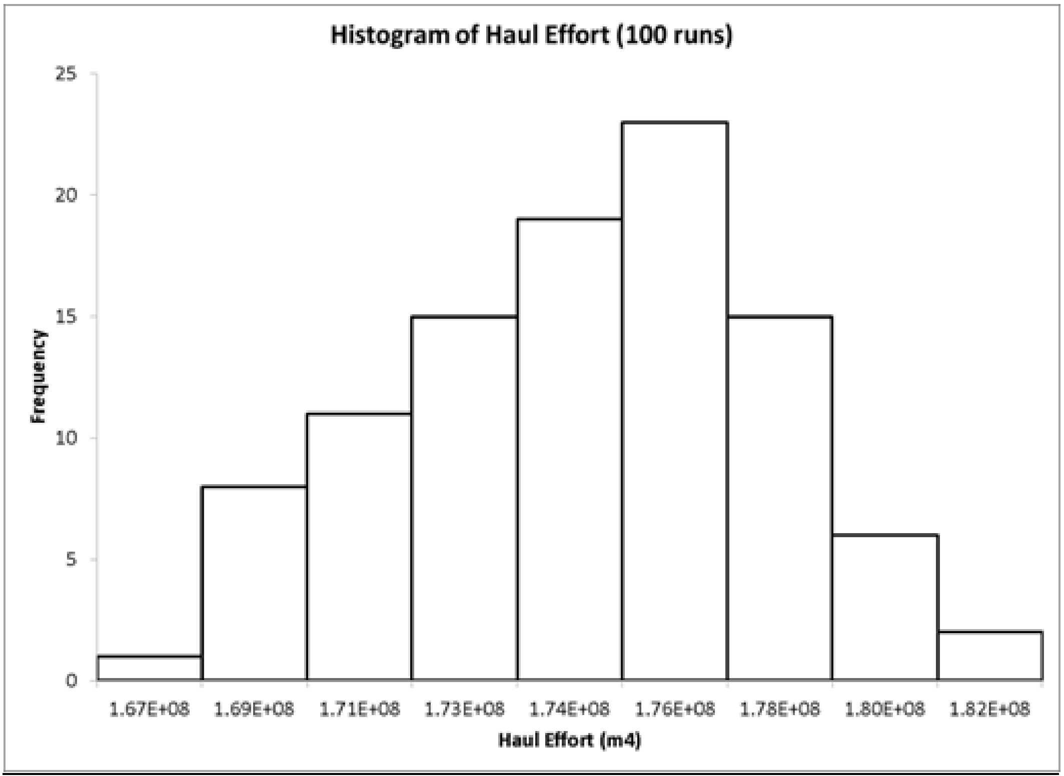

Figure 3-7: Histogram of haul effort for 100 simulation runs

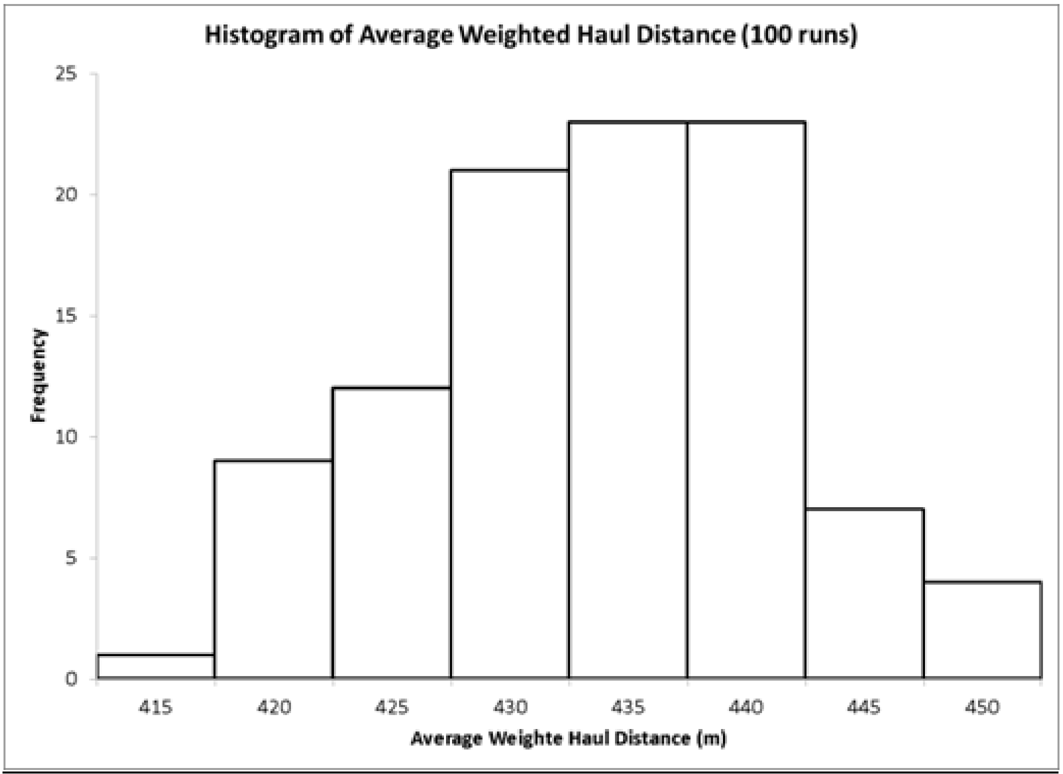

Figure 3-8: Average weighted haul distance for 100 simulation runs

The variation on the total haul effort, and in turn, the average weighted haul distance in the 100 simulations fall well within the range imposed by the precision limit of the inputted data. As the original ground surface is built using a 100 m grid, the maximum precision of any calculated distance is ±50 m. Hence, the variation on the average weighted haul distance based on simulation experiments is limited to the range [413 m, 450 m]. Note the 414 m returned from executing the proposed heuristic algorithm on 100 m grids fall in this range and close to the lower end. This further corroborates (1) the performance of the heuristic algorithm being proposed is satisfactory by producing shorter average haul distance; (2) the quantitative argument made earlier that the average weighted haul distance for a balanced site grading plan, like the center of mass for a rigid body, exhibits insignificant variation and can be taken as relatively stable or approximately invariant.

Fleet Selection:

When estimating and planning earthmoving projects, various charts are available that can be used to aid in the selection of the most appropriate equipment type for the hauling distance (Caterpillar Inc. 2011). After identifying practical equipment configurations, it is necessary to consider whether performing all onsite operations with one fleet, or breaking the project into separate sub hauls with multiple fleets, is more cost-effective and time-efficient. This decision can be supported by examining Figure 3-9.

Figure 3-9 is constructed by examining each specific movement of earth, which corresponds to a row in Table 3-1. The frequency of occurrence for each distance reported simply counts the volume moved. For example, the first row of Table 1 indicates that 17,496 m^3 of material was moved over 200 m. The frequency of 200 m is thus 17,496. This is done for all the rows in Table 1, and the histogram below is produced.

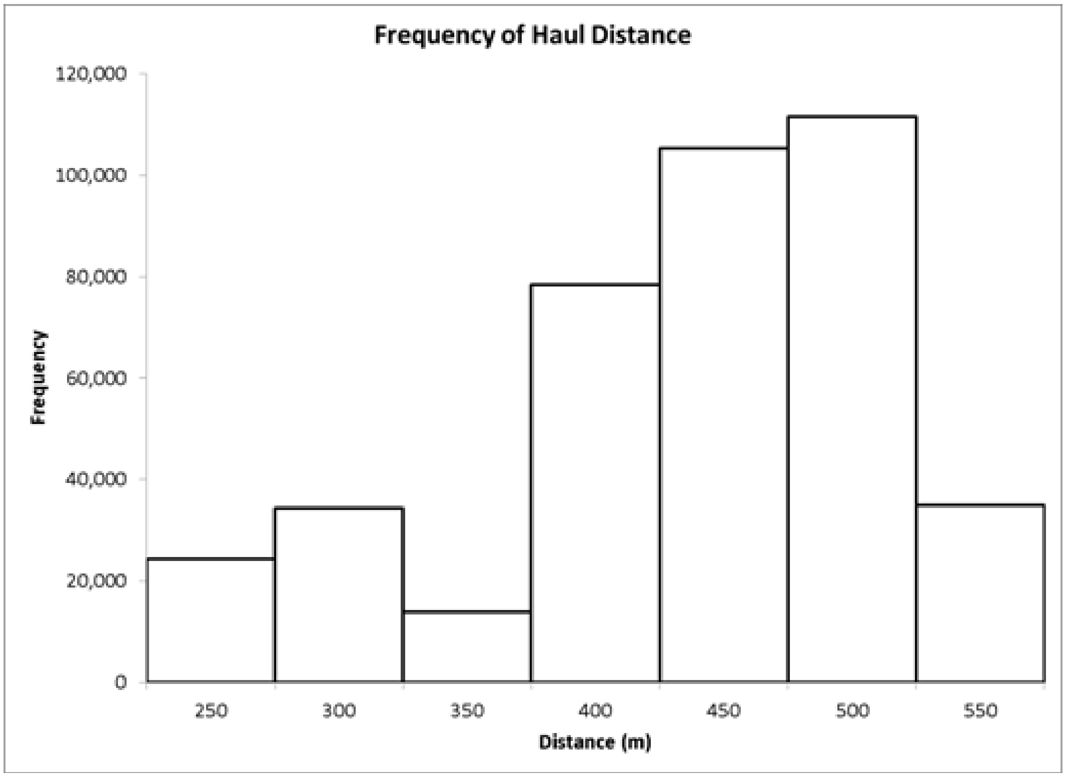

Figure 3-9: Haul distance histogram

In observing the histogram, it is clear that the average haul distance for this scenario can be considered unimodal, or single peaked, as shown below.

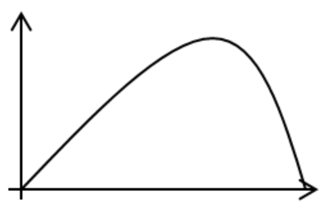
Figure 3-10: Unimodal (single peaked) distribution

Simulation of As a result, it is appropriate to estimate the project based on employing one fleet to handle all field operations. This is not to say two or more fleets cannot be selected in order to shorten project duration; however, both field supervision and project management efforts would increase substantially when multiple fleets are deployed. This also potentially increases other indirect costs such as mobilization/demobilization and adds to the risk of incurring much lower utilization of the chosen equipment. A single fleet of trucks and excavators have been identified as the equipment to be used to perform the operations for the current test case.

Project Duration:

The test case is to be carried out using one excavator with the following specifications:

Table 3-3: Cycle times and capacity for excavator

Capacity (bm3)	Min (min)	Mode (min)	High (min)
2	0.17	0.30	0.40

And 8 bm^3 capacity trucks have the following speeds:

Table 3-4: Truck speeds

Parameters	km/h	m/min
Minimum	24	400
Mode	43	717
Maximum	48	800

Three cases were considered, namely: using one truck, using two trucks and using three trucks, all with one excavator. Two simulation models were developed, namely: one detailed model considering all individual material movements, as presented in Table 3-1, using custom code written in MATLAB (MATLAB, 2012); the other simplified model developed in Simphony's general purpose template (Simphony.NET 4.0, 2012) which factors in only the average weighted haul distance of 414 m and the total volume to be moved, 402,942 bm^3. Both models incorporate dumping time in the hauling time distributions. The simple simulation model is shown below:

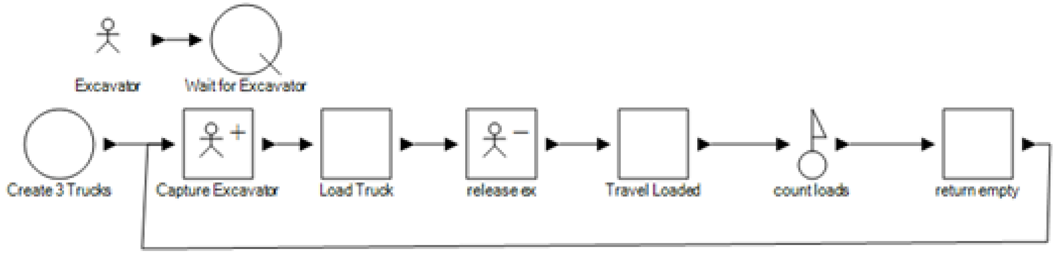

Figure 3-11: Simple Simphony simulation model

The detailed model implemented in MATLAB is too complex to be shown in a simple diagram. The code can be found in Appendix B. For each case, the project duration in working hours over ten simulation runs was kept. The results are presented below:

Table 3-5: Results of detailed and simplified simulation models

Number of trucks	Detailed model Mean (h)	Detailed model Standard deviation	Simplified model Mean (h)	Simplified model Standard deviation	Percent difference
3	1130.7	0.2	1130.1	0.7	0.1%
2	1259.6	0.4	1217.1	0.6	3.4%
1	2419.1	1.0	2327.8	1.0	3.8%

Due to the nature of earthmoving operations, a difference of less than 4% on mean project duration is deemed insignificant. As such, it can be concluded that the project durations provided by the simplified model, using only the average weighted haul distance and volume as inputs, are, for all intents and purposes, equivalent to the project durations resulting from the counterpart of a detailed simulation model. The detailed simulation model, while effective for this case, is not flexible to be adapted to a new scenario by a construction engineer who is not versed in a particular coding language or simulation tool. Additionally, as the size of the project increases (more movements), both the model building time and the simulation run-time for the detailed simulation would increase substantially, whereas the simple model remains relatively constant. As the cost quickly outweighs the benefit, this partly accounts for why it becomes impractical, expensive and unrealistic to perform a detailed simulation in practice. Nonetheless, the simplified simulation model based on determination of the average weighted haul distance can overcome such practical hurdles in application time and cost, while still providing similar benefits.

Using One or More Fleets:

Had the original haul distance histogram exhibited a larger frequency between 250-300 m in Figure 3-9, the distribution would become bimodal, or double peaked, as shown below:

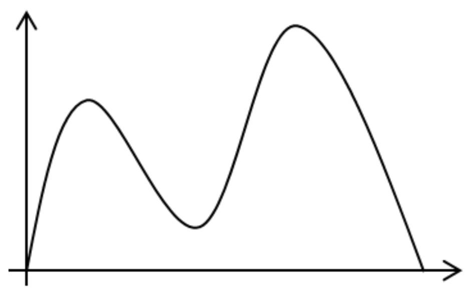

Figure 3-12: Bimodal (double-peaked) distribution

In such a case, the project could be broken into two separate operations to handle different haul distances, one for the smaller peak value, and the other for the larger peak value. One would separately calculate the average weighted haul distance for both operations. As such, the proposed method can then be applied to each operation independently in order to simplify fleet matching. For example, it would be better to use excavators and rigid haulers for the second peak, which has a longer average haul distance, while employing dozers to directly push the material for the first peak associated with a shorter average haul distance. In light of the large variance in haul distances, utilizing a single fleet solution would be either a compromise between the two haul-distance modes or ideal for one mode but unsuited for the other. In either case, the efficiency of the earthmoving operations would likely suffer.

Real World Case:

To demonstrate the application of the proposed method, a real world site grading problem located near Edmonton, AB was considered. The site size is approximately 400 m by 400 m.

The original survey elevation points were exported from AutoCAD to Microsoft Excel and coordinate transform from global easting, northing to the local site x, y was performed. From the transformed survey data, MATLAB's built-in *griddata* function was used to create the existing ground surface profile, as shown in Figure 3-13:

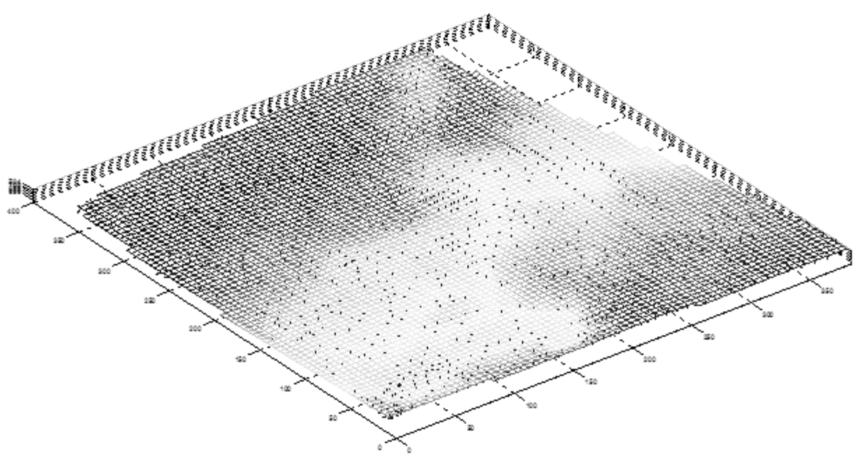

Figure 3-13: Existing Ground Surface Elevation Grid

The cut and fill balancing analysis has produced the as-designed ground surface model, factoring in (1) grading requirements for effective drainage and erosion prevention (eighteen slopes are considered) and (2) engineering constraints for positioning different geotechnical structures at different locations on site (e.g. the floor slab elevation). Because the topology is more complex than the previous test case, 20 m grid width is applied for calculating earth volumes and determining the average haul distance. The total volume of earth moved (from cut to fill) is 81,632 bm^3. By applying the proposed approach, the average haul distance is determined as 192.29 m.

Table 3-6: Simulation Results for thirteen excavator-truck fleet matching scenarios

Scenario	**Quantity of excavators**	**Type of excavator**	**Quantity of trucks**	**Duration (h)**	**Cost ($)**
1	2	320	4	258.2	381,050
2	3	320	6	171.44	332,550
3	4	320	8	128.60	338,180
4	2	336	4	150.70	254,720
5	3	336	6	100.46	252,690
6	4	336	8	75.34	232,410
7	5	336	10	60.28	256,530
8	2	345	6	115.28	260,480
9	3	345	9	77.27	237,280
10	4	345	12	57.63	255,700
11	1	385	3	198.50	292,790
12	2	385	6	97.50	258,810
13	3	385	9	65.03	269,980

Utilizing the average haul distance and the most likely cycle time data of relevant equipment found in the Caterpillar Performance Handbook Ed. 41 (Caterpillar Inc. 2011), simplified simulation models were rapidly built and executed. The possible single-fleet provision scenarios were evaluated based on simulation results (Table 3-6). The best fleet for the present case is identified as eight gravel trucks plus four CAT 336 excavators, which yields the lowest cost of $232,410 and project duration of 75.34 h. Next, the project duration for the optimum fleet configuration was further verified using a detailed simulation code written in MATLAB, which considered the exact grid-to-grid distances in order to determine the travel distance and time of a truck in each earthmoving job. The detailed simulation model was run for 10 runs, returning mean duration of 74.68 h with a standard deviation of 0.0306 h. In short, the project duration resulting from the simplified modeling approach based on the average haul distance (i.e. 75.34 h) closely matches that obtained from the detailed simulation model (74.68 h).

CONCLUSIONS:

In reviewing past research, the popularity, success, and longevity of using simulation to aid in the decision support process for earthmoving operations is obvious. In order to be able to apply the advances in simulation optimization developed in the academic world to the earthmoving industry, improvements are needed to streamline resource demands, both in time and expertise, of current simulation practices, while maintaining accuracy. Given the complexities and constant changes in field operations, we identify one major bottleneck to adopting simulation modeling in the heavy and civil construction field: it is rare to find personnel in this industry who possess both simulation knowledge and necessary field experience, who also have sufficient time to implement simulation modeling as effective decision support tools given the limited time period available for estimating and planning earthmoving operations. This accounts for our observation that simulation is much desired but not often applied in the field.

This paper presents a new meta-level rule to aid in simulating earthmoving operations. It is clearly shown that the average weighted haul distance can be used as a critical input for building a simplified simulation model, in place of a detailed simulation model which considers specific earth movement patterns, while still producing outputs of comparable accuracy. The average weighted haul distance is shown to be of the same form as the center of mass for a rigid set of particles, and was confirmed to be invariant for a given existing and proposed ground elevation based on simulation experiments on a test case. Additionally, the average haul distance can be used to provide decision support in determining whether to perform all earthwork operations with one fleet, or whether to divide the project into sub hauls with multiple unique fleets. This allows the benefits of simulation to be achieved without incurring long modeling time and high application cost associated with the construction of a detailed simulation model.

GPS technology and real time data collection are certainly valuable tools for earthmoving operations. In the planning and estimation stages of an earthmoving project, current practice generally collects original ground elevation data used for site grading design by utilizing the real time kinematics (RTK) GPS survey technology. This technology provides point coordinates on a site grid layout for ensuing design and construction analysis. The proposed new approach indeed is intended to augment the GPS survey technology with integrated analysis of site design and method design, aiding construction engineers in constructability analysis and determination of fleet selection, project execution planning, project duration or project cost.

In short, the use of the average weighted haul distance can be viewed as a step towards meta-modeling for earthmoving operations. As demonstrated in a test case and a real world case, the power of simulation is more easily accessible and allows for more rapid, straightforward applications, as the necessity for specific simulation knowledge and training becomes less of an obstacle to industry personnel. The cost of performing simulation is decreased while the benefit it provides is largely kept. Future research may focus on the identification of other invariant factors in other aspects of earthmoving and in other construction domains.

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Chapter 4: Utilizing Simulation Derived Quantitative Formulas for Accurate Excavator Hauler Fleet Selection[1]

INTRODUCTION

The lack of application of discrete event simulation (DES) by field planners in the earthworks industry can be attributed to lack of knowledge of and training for the simulation tools available; however, a more likely scenario is that industry personnel are aware of the tools, but realize the difficulty in applying them due to the dynamic nature of their work. As a result, field planners default to use of average production rates, which does not provide the accuracy desired for successful project planning and completion. Accurate fleet selection is critical for ensuring timely completion of major projects, as generally, earthworks must be completed before other activities on site can start. As a result, any delay in the earthworks operations can have major, lasting, negative impacts on the overall schedule.

For earthwork operations, many different types of equipment combinations can be considered and applied. A popular option is the use of excavators to excavate and load trucks, which then haul the material to its final location. Due to the complex interactions of both the excavators and the trucks it can be time consuming and resource intensive to examine the operations in detail. As a result, the industry often applies general deterministic approaches, in

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particular, the use of average production rates as in Peurifoy and Oberlender (2004) and the Caterpillar Performance Handbook Ed. 41 (2011), in order to determine the number of haulers required, as shown in Equation 4-1:

$$N_T = \frac{P_{ex}}{P_T} \qquad \text{Eq. 4-1}$$

where P_{ex} is the production rate of the excavator in bank cubic meters per hour (bcm/hr), P_T is the production rate of the truck (bcm/hr) and N_T is the number of trucks required. It is common practice to consider the case of rounding N_T up and N_T down to an integer value and using a cost analysis to finalize the suggested number of trucks. The production rate of the truck can be determined as in Equation 4-2:

$$P_T = \frac{V_T}{C_T} \qquad \text{Eq. 4-2}$$

where V_T is the truck volume (bcm) and C_T is the total cycle time of the truck (h) which can be calculated as in Equation 4-3:

$$C_T = \text{loading time} + \text{roundtrip travel time} + \text{dumptime} \qquad \text{Eq. 4-3}$$

The duration of the project can then be calculated by dividing the quantity to be moved by either the production of the excavator or the production of the trucks $(N_T P_T)$, whichever is lower. It has previously been shown that this approach can be inaccurate and provides misleading decision support advice in regards to fleet selection. A poorly selected fleet greatly reduces the chances of success for an earthwork operation.

Substantial research has been conducted in order to devise cost-effective quantitative methods and assist in determining the most appropriate fleet configuration for an earthmoving project. Touran and Taher (1988) applied queuing theory to select the optimum fleet size using constant time duration inputs. Shi and AbouRizk (1994, 1998), Smith et al. (1995), Hajjar and AbouRizk (1997), Martinez (1998), Marzouk and Moselhi (2002a, 2003b) and Alshibani and Moselhi (2012) applied DES to earthmoving operations. Christian and Xie (1996) constructed and used an expert system to determine the most appropriate fleet. Gransberg (1996) used a deterministic method of dividing the cycle time by the loading time of the trucks in order to determine the required number of haulers. Shi (1999) and Schabowicz and Hola (2007) used neural networks in order to determine the number of haulers required for a particular excavator. Smith (1999) estimated the productivity of earthmoving operations using linear regression techniques. Marzouk and Moselhi (2002b, 2003a, 2004) and Moselhi and Alsihibani (2009) applied genetic algorithms to determine the earthmoving fleet. Han et al (2008) applied simulation and multiple regression analysis for planning earthmoving systems. Zhang (2008) used particle swarm optimization for multi-objective optimization of earthmoving operations. Cheng et al. (2011) applied a perti net model for earthmoving operations.

Yet, the method of average production rates (Peurifoy and Oberlender, 2004) is still widely taught at post-secondary institutions and is the most predominantly applied method in the field. This can be directly attributed to the ease of application. With this in mind, we present a new early stage fleet selection and estimating method which uses simulation to derive quantitative formulas accounting for the effect of distance and volume to be moved on earthwork project durations and the required resources. This method maintains the accuracy associated with detailed simulation models, far surpassing the accuracy of using classic average production rate techniques, while allowing repeatability not often found in simulation (Kannan et al. 2000) and maintaining the ease of application by front line personnel who may not have appropriate simulation training or cannot afford the time required for simulation modeling. To accommodate the changing situations from project to project, different quantitative formulas can be constructed in order to sufficiently address the range of work normally encountered by a specific contractor. These formulas can then be applied as easily and quickly as average production rates, and require much less time and resources than construction of a detailed simulation model.

In high-risk scenarios or other complicated situations where a detailed simulation model is desired, the formulas serve as starting points in evaluating different fleet configurations, reducing the number of options to be considered. This correlates directly with reducing simulation time and resources.

The new approach is applied to determine the required excavator and hauler fleet for a known volume and haul distance earthmoving operation. The approach is compared with average production rates and detailed simulation. The "danger" associated with using average production rates is clearly illustrated, and situations where detailed simulation is required or should be applied are clearly identified. This new method does not replace detailed simulation, but rather compliments and assists in detailed simulation, offering an easier path of implementation in industry. At least, the insight gained points out great room for improvement in the current practice of using average production rates.

CONSTRUCTION OF THE FORMULAS

Excavation Time

The excavation time for a large volume of material can be approximated by a continuous function as in Equation 4-4:

$$F_V = \frac{\mu_{\mathrm{dist}} N_B}{T_C} \qquad \text{Eq. 4-4}$$

where F_V, is the duration in minutes for one bank cubic meter of material to be excavated and loaded, μ_{dist} is the average of the supplied cycle time distribution of the specific excavator in minutes, N_B is the number of buckets required to fill the truck and T_C is the capacity of the truck in bank cubic meters.

Number of Trucks Required

The number of trucks required to ensure the excavator is the governing resource, defined as the resource that limits system production, is dependent on the specific excavator being used, the specific truck type being considered and the haul distance. A continuous function, F_D, is constructed for each excavator and truck combination, using custom Monte Carlo simulation code implemented in MATLAB. A flowchart of the simulation is shown in Figure 4-1:

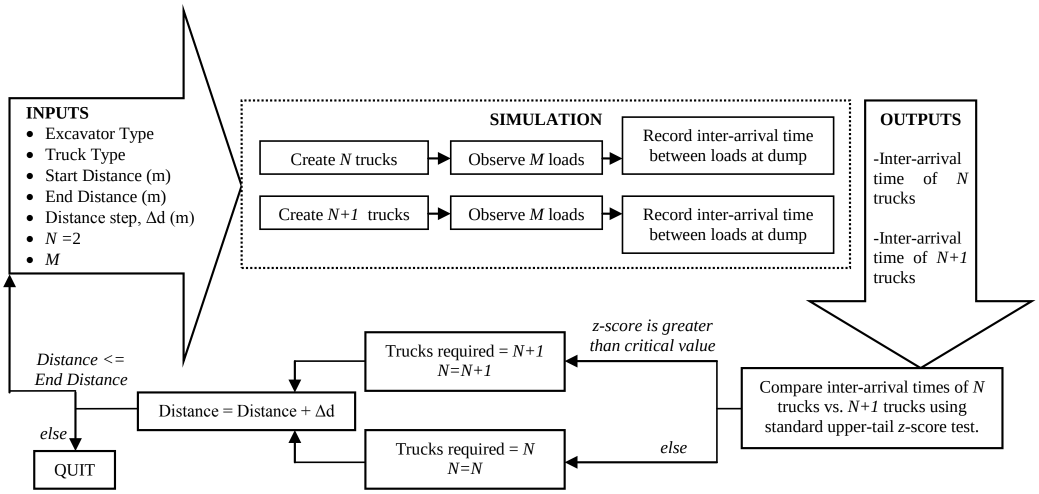

Figure 4-1: Simulation Flowchart

The simulation starts with the number of trucks, N, equal to two, and the haul distance set to ensure the excavator will be the limiting resource. This is confirmed using the z-score test, described later. The simulation observes M dumped loads for two cases: 1) hauling with N trucks and 2) hauling with $N+1$ trucks. The mean and variance of the inter-arrival time of the dumped loads are calculated for both cases. The distance is then increased by a step, Δd. Dump time is considered to be integrated with the travel time of the trucks. A standard one-sided z-score test with 95% confidence is then used to determine if the mean inter-arrival times of both cases cannot be considered equal. The z-score statistic is calculated as shown in Equation 4-5:

$$Z = \frac{\mu_N - \mu_{N+1}}{\sqrt{\frac{\sigma_N^2 + \sigma_{N+1}^2}{n}}} \qquad \text{Eq. 4-5}$$

where μ_N is the mean inter-arrival time for N trucks, σ_N^2 is the variance of the inter-arrival time for N trucks, μ_{N+1} is the mean inter-arrival time for $N+1$ trucks, σ_{N+1}^2 is the variance of the inter-arrival time for $N+1$ trucks and n is the number of observations. If the returned z-statistic is greater than 1.645, then $N + 1$ trucks are required at the current distance to ensure that the excavator is the governing resource. N is then equal to $N + 1$ and the simulation is repeated at the next distance, $d + \Delta d$.

The results are recorded to identify the largest haul distance where the excavator is the governing resource for each specific number of trucks and plotted as the number of trucks vs. distance and a linear regression performed in order to obtain a quantitative, continuous formula, F_D, which takes for input the haul distance and returns the number of trucks required for the excavator to be the governing resource. The confidence interval of the returned y value of the regression, the required number of trucks for a given distance, is determined as in Equation 4-6:

$$\Delta y_{CI,i} = t_{\frac{\alpha}{2},df} e_y \sqrt{\frac{1}{n} + \frac{(x_i - \bar{x})^2}{\sum_{i=1}^{n}(x_i - \bar{x})^2}} \qquad \text{Eq. 4-6}$$

where $t_{\frac{\alpha}{2},df}$ is the t-value for a specified confidence level of $(1 - \alpha)$ with df, degrees of freedom, e_y is the standard error of the y variable, $df = n - 2$, and $\bar{x}$ is the mean of the x values.

Calculating Project Duration and Project Cost

The total cost of the earthmoving operation can be calculated as in Equation 4-7:

$$C_T = C_M + C_E + C_O \qquad \text{Eq. 4-7}$$

where C_T is the total cost ($), C_M is the cost to import/export material ($), C_E is the cost due to equipment and C_O is the overhead cost of the project. C_M is calculated as in Equation 4-8:

$$C_M = C_i M_i + C_e M_e \quad \text{Eq. 4-8}$$

where C_i is the cost to import one loose cubic meter of material ($), C_e is the cost to export one bank cubic meter of material ($), M_i is the amount of material in loose cubic meters to be imported, M_e is the amount of material in bank cubic meters to be exported.

To calculate the equipment cost, C_E, and the overhead cost, C_O, two cases need to be considered: 1) the excavator as the governing resource, and 2) the trucks as the governing resource.

EXCAVATOR AS THE GOVERNING RESOURCE

In the case of the excavator being the governing resource, the duration of the project depends directly on the amount of time required for the excavator to excavate and load the material. The duration in this case can be calculated as in Equation 4-9:

$$\text{duration(h)}=\frac{EF_V V_T}{60N_{ex}} \quad \text{Eq. 4-9}$$

where V_T is the total amount of material in bank cubic meters to be moved, N_{ex} is the number of excavators to be used and E is the efficiency factor. The equipment cost, C_E, can then be calculated as in Equation 4-10:

$$C_E = \frac{EF_V V_T}{60N_{ex}}\left[\lceil F_D(\varphi)\rceil N_{ex}C_t + N_{ex}C_{ex} + C_d + C_g + C_c\right] + C_s \quad \text{Eq. 4-10}$$

where $F_D(\varphi)$ is the required number of trucks at the given average haul distance, φ, in meters, C_t is the hourly cost for the selected trucks ($), C_{ex} is the hourly cost for the selected excavator ($), C_d is the hourly cost for the selected dozer ($), C_c is the hourly cost for the selected compactor ($), C_g is the hourly cost for the grader ($), C_s is the associated flat rate setup cost for the equipment ($). The overhead cost, C_O, can be calculated as in Equation 4-11:

$$C_O = C_I \frac{EF_V V_T}{60 N_{ex} D_H} \quad \text{Eq. 4-11}$$

where C_I is the daily indirect cost ($) and D_H is the hours per day to be worked.

TRUCKS AS THE GOVERNING RESOURCE

The calculations in the case where the trucks are the governing resource are more complicated than in the case of the excavator being the governing resource. It is noted that there exists a haul distance, call it F_{D*}, where the production rates for both the excavator and the specific number of trucks are precisely matched. F_{D*} can be calculated by taking the appropriate formula for F_D, inputting the number of trucks, and solving for the distance, and therefore, the following relationship holds:

$$\frac{1}{F_V} = T_C N_T \left(\frac{\#\text{ trips}}{\text{min}}\right) \quad \text{Eq. 4-12}$$

where T_C is the capacity of the truck in bank cubic meters, and N_T is the number of trucks to be used. Then:

$$\frac{\text{min}}{\text{trip}} = F_V T_C N_T \quad \text{Eq. 4-13}$$

The average speed of the trucks, in meters per minute, for the cycle can then be calculated as:

$$T_{\text{speed}} = \frac{d}{t} = \frac{2F_{D*}}{F_V T_C \lfloor F_D(\varphi) \rfloor} \quad \text{Eq. 4-14}$$

And the truck cycle time as:

$$T_{\text{cycle}} = \frac{2\varphi}{T_{\text{speed}}} \quad \text{Eq. 4-15}$$

The duration of the project can then be calculated as:

$$\begin{aligned} \text{duration(h)} &= \frac{V_T}{(\lfloor F_D \rfloor) T_C N_{ex}} \times \frac{T_{\text{cycle}}}{60} \\ &= \frac{V_T}{(\lfloor F_D \rfloor) T_C N_{ex}} \times \frac{2\varphi}{60 T_{\text{speed}}} \\ &= \frac{V_T}{(\lfloor F_D \rfloor) T_C N_{ex}} \times \frac{2\varphi}{60 \left(\frac{2F_{D*}}{F_V T_C \lfloor F_D \rfloor} \right)} \\ \text{duration(h)} &= \frac{E V_T F_V \varphi}{60 F_{D*} N_{ex}} \end{aligned} \quad \text{Eq. 4-16}$$

Knowing the project duration allows for calculation of the equipment cost, C_E, and the overhead cost, C_O. C_E is calculated as in Equation 4-17:

$$C_E = \frac{E V_T F_V \varphi}{60 F_{D*} N_{ex}} \left[\lfloor F_D \rfloor N_{ex} C_t + N_{ex} C_{ex} + C_d + C_g + C_c \right] + C_s \quad \text{Eq. 4-17}$$

C_O is calculated as follows in Equation 4-18:

$$C_O = C_I \frac{E V_T F_V \varphi}{60 F_{D*} N_{ex}} \quad \text{Eq. 4-18}$$

The dozer and compactor are selected automatically by looking at the overall production rate of the system. The production rate is calculated as in Equation 4-19:

$$\text{overall production rate} = \frac{\text{total volume to be moved (bcm)}}{\text{duration of the project (h)}} \qquad \text{Eq. 4-19}$$

VALIDATION OF THE METHOD THROUGH CONSIDERATION OF A TEST CASE

The earthwork haul to be considered involves an average haul distance of 3 km and 100,000 bank cubic meters of material to be moved. The material considered has no appreciable swell. One fleet will be used to perform the work. Four excavators are considered to perform the earthwork operations. Specifications were taken from the Caterpillar Performance Handbook Ed. 41 (2011) and can be found below. For all four excavators, the amount of time required to excavate and load one cubic meter of material into a 6.12 bank cubic meter capacity tandem axel gravel truck, F_V, was calculated. Additionally, F_V was also calculated for loading an 18.5 bank cubic meter capacity articulated truck. An efficiency factor of 100% was considered. It should be noted that if the same efficiency factor is applied to the trucks and the excavator, the factor is cancelled out in the calculation of the fleet size. Note that N_B stands for number of buckets to fill.

Table 4-1: Excavator Capacity and Cycle Times

Excavator	Capacity (bm^3)	Min (min)	Mid (min)	High (min)	Avg (min)	N_B GT	F_V GT	N_B RT	F_V RT
CAT 320	0.84	0.17	0.30	0.40	0.29	8	0.38	22	0.34
CAT 336	1.53	0.23	0.33	0.45	0.34	4	0.22	12	0.22
CAT 345	2.29	0.2	0.33	0.48	0.34	3	0.17	8	0.15
CAT 385	3.82	0.2	0.40	0.70	0.43	2	0.14	5	0.12

The 6.12 bank cubic meter capacity trucks (GT) were considered to have the following speeds, represented by a triangular distribution. No differentiation was used between loaded and empty haul speeds.

Table 4-2: Gravel Truck Speeds

Parameter	km/h	m/min
Min	24	400
Mode	43	717
Max	48	800

The 18.5 bank cubic meter capacity articulated trucks (RT) were considered to have the following speeds, represented by a triangular distribution. Again, specifications were taken from the Caterpillar Performance Handbook Ed. 41 (2011).

Table 4-3: Rock Truck Speeds

	loaded		unloaded	
Parameter	km/h	m/min	km/h	m/min
Min	13	220	28	467
Mode	24	400	43	720
Max	56	933	58	960

Using the above information, F_D was constructed for each excavator and truck combination. The simulation was tested using two different random number generators available in MATLAB, the Mersenne twister and the combined recursive algorithm. In order to ensure repeatability of the results, 100 million observations were required. The associated graphs for the case of the excavators with the rock trucks can be found below (Figure 4-3).

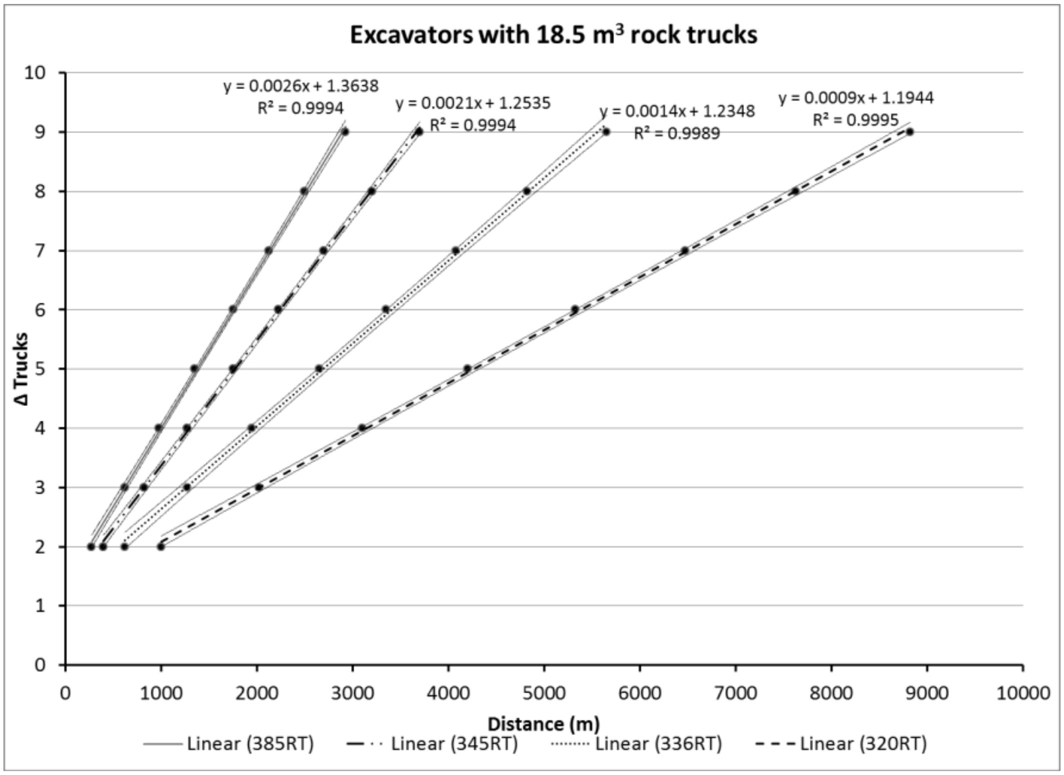

Figure 4-2: Required Number of Rock Trucks by Haul Distance

Table 4-5 identifies the hourly rates and associated setup costs for all equipment considered to move the material.

Table 4-5: Setup and Hourly Costs for Various Equipment

Equipment	Hourly Rate ($)	Setup ($)
320 Excavator	155	2500
336 Excavator	215	3000
345 Excavator	250	3500
385 Excavator	394	4000
6.12 m^3 truck	120	240
18.5 m^3 truck	200	3000
CP323	103	2000
CP433	133	2000
CP56	150	2000
D6N	172	2000
D6T	196	2000
D7T	219	2500
D8T	265	2500
D9T	328	3000
14H	235	500

As mentioned earlier, the dozer and packer are selected automatically by looking at the overall production rate of the system. The maximum capabilities of the dozer and packer have been determined from data in the Caterpillar Performance Handbook Ed. 41. (2011) and are shown in Table 6. If the production rate required is greater than the largest available machine, then multiples of the largest machine are used. It is assumed that one 14H grader is always necessary on site.

Table 4-6: Production Capabilities of Various Dozers and Compactors

Equipment	Type	Production (bm^3/h)
CP323	Compactor	239
CP433	Compactor	326
CP56	Compactor	847
D6N	Dozer	500
D6T	Dozer	700
D7T	Dozer	900
D8T	Dozer	1050
D9T	Dozer	1700

Various fleet configuration options were analyzed using the method presented above. The total cost calculated for each option involved only equipment costs; indirect and material costs are not considered, but can easily be considered by applying Equation 4. The lowest cost option was found to be two 345 excavators with fourteen rock trucks, one CP56 compactor, one 14H grader and one D7T dozer for a cost of $589,238.

For all locally optimal fleet configurations (the lowest cost using a specific excavator and truck type), individual simulation models were built using the CYCLONE template in Simphony (Simphony.NET 4.0, 2012). An example is shown below using six 320 excavators with 36 gravel trucks. Each unique excavator is assigned six specific gravel trucks. A truck can only begin to load when its assigned excavator is available. Once loading is completed, the excavator can begin loading another truck and the loaded truck begins the hauling task. Once unloaded, the truck moves into the return task. After the return task, the truck load is counted. All trucks loads of all excavators are counted together. The truck queues and waits for its assigned loading unit to be available.

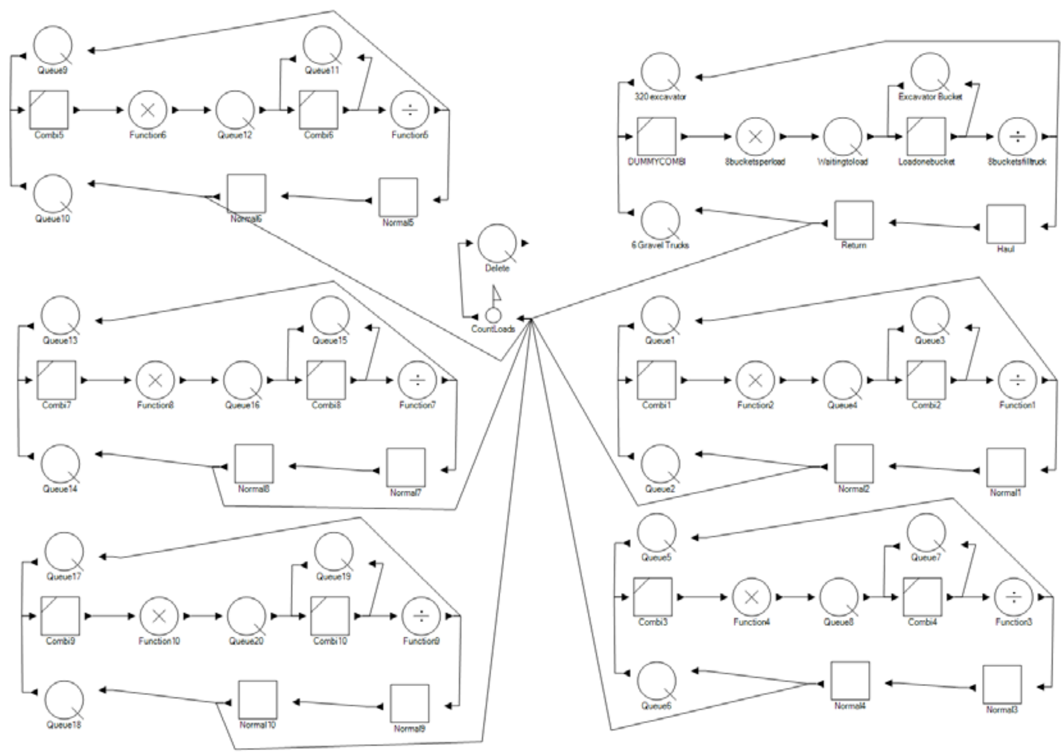

Figure 4-3: CYCLONE Model, Six 320 Excavators with 36 Gravel Trucks

Durations obtained using Equation 4-6, when the excavator was the governing resource, and Equation 4-13, when the trucks were the governing resource, were compared with the mean duration of ten simulation runs and the % difference calculated. Results can be found in Table 4-8.

Table 4-8: Quantitative Formulas vs. Classic Simulation

Ex.	# of Ex.	Truck	Lim. Res.	Trucks Req. (quantitative formulas)	Dur. (h) (eq. 9/16) (1)	Dur. (h) Simulation (2)	% diff (1) vs. (2)
320	5	GT	EX	35	127	127	0
320	6	GT	Truck	36	126	108	16
336	3	GT	EX	36	122	122	0
336	3	GT	Truck	33	124	122	1
345	2	GT	EX	30	142	138	3
345	2	GT	Truck	28	148	138	7
385	3	GT	EX	54	78	79	1
385	3	GT	Truck	51	78	79	1
320	4	RT	EX	16	142	144	2
320	7	RT	Truck	21	121	90	30
336	3	RT	EX	18	122	122	1
336	3	RT	Truck	15	136	122	11
345	2	RT	EX	16	125	122	3
345	2	RT	Truck	14	137	122	12
385	1	RT	EX	10	200	195	2
385	1	RT	Truck	9	204	195	4

The number of trucks required and the associated duration for various fleet configurations were also calculated using the average production rate approach as found in Peurifoy and Oberlender (2004). Specific calculations can be found in Table 4-9.

Table 4-9: Trucks Required by Applying Classic Average Production Rates

Ex.	Avg. Bucket Cycle Time (min)	Truck	N_B	Time Req. to Fill Truck (min)	Ex. Prod. Rate (bm^3/min)	Ex. Prod. Rate (bm^3/h)	Avg. Truck Speed (m/min)	Truck Travel Time (min)	Truck Cycle Time (min)	Truck Prod. Rate (bm^3/h)	Trucks Req. per Ex.
320	0.29	GT	8	2.32	2.64	158.28	639	9.39	11.71	31.36	5.05
336	0.34	GT	4	1.36	4.50	270.00	639	9.39	10.75	34.16	7.90
345	0.34	GT	3	1.02	6.00	360.00	639	9.39	10.41	35.27	10.21
385	0.43	GT	2	0.86	7.12	426.98	639	9.39	10.25	35.83	11.92
320	0.29	RT	22	6.38	2.90	173.98	623	9.63	16.01	69.35	2.51
336	0.34	RT	12	4.08	4.53	272.06	623	9.63	13.71	80.99	3.36
345	0.34	RT	8	2.72	6.80	408.09	623	9.63	12.35	89.91	4.54
385	0.43	RT	5	2.15	8.60	516.28	623	9.63	11.78	94.26	5.48

The duration can be calculated using the average production rate approach as in Equations 4-20 and 4-21. When the excavator is the governing resource:

$$\text{dur. (h)} = \frac{\text{vol. to be moved (bm}^3\text{)}}{\text{\# of excavators} \times \text{excavator production rate (bm}^3\text{/h)}} \quad \text{Eq. 4-20}$$

And when the trucks are the governing resource:

$$\text{dur. (h)} = \frac{\text{vol. to be moved (bm}^3\text{)}}{\text{\# of trucks} \times \text{truck production rate (bm}^3\text{/h)}} \quad \text{Eq. 4-21}$$

The results were then compared with the mean duration of ten simulation runs and the % difference calculated. Results can be found in Table 10.

Table 4-10: Average Production Rates vs. Classic Simulation

Ex.	# of Ex.	Truck	Lim. Res.	Trucks Req. (classic)	Dur. (h) Classic (3)	Dur. (h) Simulation (classic) (4)	% diff (3) vs. (4)
320	5	GT	EX	30	126	129	2
320	6	GT	Truck	30	106	122	14
336	3	GT	EX	24	123	141	14
336	3	GT	Truck	21	139	159	13
345	2	GT	EX	22	139	151	8
345	2	GT	Truck	20	142	163	14
385	3	GT	EX	36	78	90	15
385	3	GT	Truck	33	85	97	14
320	4	RT	EX	12	144	156	8
320	7	RT	Truck	14	103	126	20
336	3	RT	EX	12	123	137	12
336	3	RT	Truck	9	137	176	25
345	2	RT	EX	10	123	149	20
345	2	RT	Truck	8	139	182	27
385	1	RT	EX	6	194	240	21
385	1	RT	Truck	5	212	282	28

CONCLUSIONS

Excavator as the Governing Resource

For the case of the excavator as the limiting resource, the newly presented simulation derived quantitative formulas provide outputs that are for all intents and purposes equal to the outputs provided by the detailed simulation models. While derivation of the quantitative formulas does take time, the investment to do so can be easily justified by the repetition of use that they provide unlike detailed simulation models which are generally only applied once or twice before needing modification. Additionally, the formulas provide the opportunity for rapid deployment at the field level as essentially no simulation knowledge is required and can be applied simply through paper and pencil. The quantitative formulas offer the same simplicity as the classical average production rate with the accuracy found in detailed simulation models.

It must be noted that the classic average production rate method results in selection of fleets that are (1) severely under-trucked, (that is to say that there are not enough trucks selected to actually result in achieving the duration estimated by the method) and (2) underestimated in terms of project duration given the identified fleet (underestimated as much as 28%). This is a significant danger, as often, fleet allocation is made earlier in project planning and for most resource constrained contractors later acquisition/mobilization of more trucks to site can invoke significant unplanned and unforeseen costs, which are needed as trade-off to recover the project schedule. By offering a solution that is impossible to achieve in reality, the use of classic average production rates is not justifiable and will entrain serious consequences.

Trucks as the Governing Resource

For the case of the trucks being the limiting resource, the quantitative formulas do suffer from similar inaccuracies as classic average production rate methods; however, there is one important difference. The use of quantitative formulas overestimates the project duration, whereas the classic average production rates once again underestimate the project duration. Again, classic average production rates methods provide fleet configuration solutions that cannot in reality obtain the estimated project duration. The solution provided by the quantitative formulas, however, can actually be obtained, in fact surpassed, in reality. It is arguable that this is the much better position to be in at the early stages of estimation and project planning.

It has been shown that for an accurate estimate of project duration when the trucks are the limiting resource, the application of detailed simulation modeling is required. The quantitative formulas shown can assist in this process, by providing a clear starting point for fleet selection. For example, by simply looking at the case of the excavator as the limiting resource, certain excavator and truck combinations may be able to be eliminated instantly without further consideration due to their high cost. Then, the remaining excavator truck combinations can be further refined through use of detailed simulation models. The starting point for each model would be one less truck for each excavator truck combination suggested by the quantitative formulas. The truck is now the limiting resource. The simulation can be run, the duration recorded and the time/cost trade-off evaluated. The process can be repeated for the suggested number of trucks less two and so forth. By this approach, the simulation expert is provided with a concrete starting point for the number of trucks to consider, and must only run simulations for scenarios with less than that number of trucks. In contrast, the early stage estimating based on classic average production rates provides no bounds relating to the true actual optimum number of trucks required.

The presented method offers a new approach to fleet selection and determination of the duration of earthmoving operations, where one fleet is applied. The application clearly illustrates that a decrease in production does not directly correlate with an increase in project cost. It is significantly more accurate than the use of classic average production rates and allows for easy early stage estimation, planning and selection of a fleet in order to maximize production while minimizing total project cost. The method also serves to compliment detailed simulation, providing a clear starting point in considering the time-cost trade-off which occurs when the excavator is no longer the governing resource in the earthmoving production system.

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Chapter 5: Conclusion and Recommendation

SUMMARY OF THESIS WORK

Based on a comprehensive literature review and consultation with a major Canadian heavy civil contractor, the thesis research has clearly identified the need for advancement in the face of inadequate current practice. In order to address this need, identification of an invariant input factor, the average weighted haul distance has been examined, allowing for easier adoption of current simulation methodologies by industry personnel. Continuing forward with this first step towards meta-modeling, new quantitative methods are proposed, using simulation to produce graphical results which can then be used in the early stage bidding process to enhance accuracy of fleet selection and to position themselves to take advantage of the optimum solution, defined as the best decision that can be made with the given input data available in the current time frame the decision is being made.

The methods were developed and validated through use of data provided by a major Canadian industrial earthworks contractor. The thesis research offers a preliminary step towards meta-modeling, allowing for accurate simulation models to be applied to a greater variety of situations and with greater ease than previous efforts.

FUTURE RECOMMENDATIONS

It is clearly shown that the accuracy of the new quantitative methods presented is much greater that past heuristic rules or existing charts displayed in resources such as the *Caterpillar Performance Handbook*. This has been achieved before by other methods, but not with the simplicity presented here.

The biggest limitation to the work presented, is its lack, as all other current methods of being able to handle dynamic change as more information for a project becomes available, the stage moving from bidding to award and execution. One possible solution to this is to produce numerous charts in advance, and to bundle them in such a way to identify which chart should be used knowing and not knowing key information. Unlike the *Caterpillar Performance Handbook*, these charts must continue to be based on real world operating scenarios.

Not every scenario imaginable will have clearly related real world data stored. Future work in simulation and mathematical modeling should look into extending the lifespan of previous optimum solutions, that is, to add a mechanism allowing for adjustment of the previous identified solution easily as more information becomes known. This is key to tying existing known solutions to previously non-encountered scenarios, and determining the reliability and accuracy of the analysis.

A more diligent procedure for moving towards an early stage solution to the final optimum solution is needed. Currently spending a great deal of effort early is not feasible due to a lack of input information or the likely scenario of over-optimising and then having a solution which is no longer valid when assumed input information changes. Later in the process, when more information is known and the project is ready to be executed, there is generally a lack of time and resource to bother reconsidering the previous solution. Furthermore, even spending a large amount of effort late in the game does not guarantee any robustness as input information can change at any given moment. There is no point that can clearly be identified as the time when it is safe to fully optimise the solution.

There are numerous factors left to be considered and addressed that affect earthmoving operations that are currently not being simulated or render modeling too complex to allow for industry adoption. Key factors pertaining to earthmoving operations have to be identified and clearly communicated to allow for both industry and academic efforts to be focused on these issues. Tools developed using these factors must be usable by the industry without additional cost in terms of time and expertise being imposed. The question that must always come to mind moving forward is how can we improve accuracy and results without any increase in cost in terms or time or expertise and in fact, can this be done while decreasing the cost.

FINAL REMARKS

The application of simulation to the heavy civil earthmoving industry has not yet reached its full potential. Numerous opportunities exist. It is hoped that this thesis will encourage closer industry and academic collaboration with the aim of making simulation and other advanced quantitative methods more utilized by industry professionals, aimed at changing industry best practice.

Appendix A: Haul Effort Detailed Calculations

The haul effort calculation based on 50 m grid on the testing case

Cut		Fill		Volume (bm^3)	Distance (m)	Effort (bm^4)
x	y	x	y			
1	12	1	4	302	400	120800
1	12	1	3	302	450	135900
1	12	9	10	2127	412.3106	876984.57
1	12	9	9	2127	427.2002	908654.8
1	12	10	10	2127	460.9772	980498.55
1	12	10	9	2127	474.3416	1008924.7
1	12	7	8	874	360.5551	315125.18
1	12	8	8	874	403.1129	352320.66
1	12	7	7	874	390.5125	341307.91
1	12	9	8	4893	447.2136	2188216.1
1	11	9	8	515	427.2002	220008.1
1	11	2	4	302	353.5534	106773.12
1	11	3	4	2633	364.0055	958426.47
1	11	2	3	302	403.1129	121740.09
1	11	4	4	2633	380.7887	1002616.5
1	11	5	5	753	360.5551	271498.01
1	11	5	6	753	320.1562	241077.63
1	11	6	6	753	353.5534	266225.7
1	11	6	5	753	390.5125	294055.9
1	11	7	6	2241	390.5125	875138.48
1	11	4	4	4989	380.7887	1899754.6
2	12	7	6	1974	390.5125	770871.64
2	12	3	4	2633	403.1129	1061396.2
2	12	9	7	5408	430.1163	2326068.8
2	12	8	6	4215	424.2641	1788273
2	12	7	5	2397	430.1163	1030988.7
2	11	7	5	1818	390.5125	709951.7
2	11	6	4	4989	403.1129	2011130.2
2	11	5	3	4989	427.2002	2131301.7
2	11	10	8	4831	427.2002	2063804.1
3	12	10	8	577	403.1129	232596.14
3	12	10	7	4437	430.1163	1908425.9
3	12	9	6	8512	424.2641	3611335.8

3	11	10	7	971	403.1129	391422.61
3	11	8	5	4215	390.5125	1646010.1
3	11	7	4	8017	403.1129	3231756
3	11	6	3	323	427.2002	137985.66
1	10	4	2	3065	427.2002	1309368.6
1	10	1	2	4597	400	1838800
1	10	2	2	4597	403.1129	1853109.9
2	10	3	2	4086	403.1129	1647119.3
2	10	4	2	7151	412.3106	2948432.8
2	10	5	2	1022	427.2002	436598.59
4	12	6	3	8512	460.9772	3923838.1
4	12	10	6	5014	424.2641	2127260
4	11	8	4	8017	403.1129	3231756
4	11	10	5	5509	424.2641	2337270.8
5	12	10	5	3003	430.1163	1291639.1
5	12	9	4	7109	447.2136	3179241.5
5	11	9	4	4896	403.1129	1973640.7
5	11	7	3	5216	412.3106	2150611.9
1	9	5	2	7593	403.1129	3060836.2
1	9	6	3	4666	390.5125	1822131.2
2	9	5	2	1301	380.7887	495406.04
2	9	7	3	2801	390.5125	1093825.5
2	9	6	2	8157	403.1129	3288191.8
3	10	8	3	8017	430.1163	3448242.1
3	10	6	2	1185	427.2002	506232.22
3	9	6	2	574	380.7887	218572.69
3	9	9	4	8628	390.5125	3369341.7
4	10	9	4	3377	390.5125	1318760.7
4	10	8	3	5825	403.1129	2348132.6
4	9	10	4	9202	390.5125	3593495.9
6	12	10	4	910	447.2136	406964.37
6	12	8	3	3377	460.9772	1556720.1
6	12	9	3	5825	474.3416	2763040.1
6	11	9	3	6180	427.2002	2640097.2
6	11	10	3	3932	447.2136	1758443.9
5	10	10	3	6107	430.1163	2626720
6	10	10	3	1966	403.1129	792519.94
6	10	7	2	4141	403.1129	1669290.5
1	7	7	2	8598	390.5125	3357626.3
1	7	1	1	86	300	25800
1	8	2	1	4597	353.5534	1625284.9

1	8	3	1	4001	364.0055	1456386
2	8	3	1	3150	353.5534	1113693.2
2	8	4	1	5448	364.0055	1983101.9
2	7	4	1	703	316.2278	222308.12
2	7	5	1	2184	335.4102	732535.87
1	6	5	1	1021	320.1562	326879.49
1	6	6	1	1353	353.5534	478357.74
3	8	6	1	5584	380.7887	2126323.9
4	8	6	1	2979	364.0055	1084372.4
1	5	7	1	4374	360.5551	1577068.1
2	5	7	1	4374	320.1562	1400363.3
2	6	7	1	4077	353.5534	1441437.2
2	6	8	1	297	390.5125	115982.21
3	5	8	1	1723	320.1562	551629.15
4	5	8	1	1723	282.8427	487337.99
4	6	8	1	1723	320.1562	551629.15
3	6	8	1	1723	353.5534	609172.49
3	7	8	1	5584	390.5125	2180621.7
4	7	8	1	52	360.5551	18748.867
4	7	8	2	5532	320.1562	1771104.2
4	8	8	2	2605	360.5551	939246.11
5	7	8	2	2702	291.5476	787761.6
6	7	8	2	1986	269.2582	534746.87
6	7	9	1	716	335.4102	240153.7
5	8	9	1	2702	403.1129	1089211
6	8	9	1	2702	380.7887	1028890.9
5	9	9	1	6107	447.2136	2731133.4
6	9	9	1	4184	427.2002	1787405.6
6	9	9	2	1923	380.7887	732256.58
7	9	9	2	2325	364.0055	846312.77
8	9	9	2	2325	353.5534	822011.63
7	10	9	2	2325	412.3106	958622.06
8	10	9	2	2325	403.1129	937237.46
7	11	9	2	5188	460.9772	2391549.8
7	11	10	1	879	522.0153	458851.47
8	11	10	1	6067	509.902	3093575.1
9	11	10	1	1529	502.4938	768312.99
10	11	10	1	1529	500	764500
10	12	10	1	1529	550	840950
9	12	10	1	1529	552.2681	844417.85
8	12	10	1	3349	559.017	1872147.9

8	12	10	2	2718	509.902	1385913.5
7	12	10	2	6067	522.0153	3167067
7	12	10	2	7626	522.0153	3980888.9
				Sum=402941		Sum=165805946

Appendix B: Custom MATLAB Simulation Code

```
        for z=1:10
            %Read in table of specific earth movements from Excel
            HOW=xlsread('Detailed.xlsx','howto');
            %Read in table of excavator specifications
            EXTABLE=xlsread('Detailed.xlsx','exsetup');
            %Read in table of truck specifications
            TRUCKTABLE=xlsread('Detailed.xlsx','trucksetup');
            task=0;
            L=0.23;
            M=0.33;
            U=0.45;
            BucketsReq=4;
            Phi=(M-L)/(U-L);
            TNOW=0;
            EVENTLIST=[];
            MAXTASK=size(HOW,1);
            GRIDSPACING=100;
            Exassigned=zeros((size(EXTABLE,1)),1);
            %while there are still tasks to handle on the list, do them
            while task<=MAXTASK
                EXAVAILABLE=find((EXTABLE(:,6))==0);
                %assign tasks to free excavators
                if isempty(EXAVAILABLE)==0 && task<MAXTASK
                    for i=1:size(EXAVAILABLE,1)
                        %make excavator no longer available
                        EXTABLE(EXAVAILABLE(i),6)=1;
                        %add task assigned
                        task=task+1;
                        %set excavator x location
                        EXTABLE(EXAVAILABLE(i),3)=HOW(task,1);
                        %set excavator y location
                        EXTABLE(EXAVAILABLE(i),4)=HOW(task,2);
                        %set the amount of dirt excavator must move to complete
                        %assigned task1
                        EXTABLE(EXAVAILABLE(i),5)=HOW(task,5);
                        %find trucks that are free to be filled (trucks will be
                        %assigned to smallest queue later but must be originally
                        %assigned)

[r,c]=find((TRUCKTABLE(:,7))==(EXTABLE(EXAVAILABLE(i),1))&(TRUCKTABLE(:,4)==0));
                        if isempty(r)==0
                            %might be more than one truck available, start with
first
                            r=r(1);
                            %record destination that truck will take the dirt
                            TRUCKTABLE(r,2)=HOW(task,3);
                            TRUCKTABLE(r,3)=HOW(task,4);
                            %record destination trucks started from
                            TRUCKTABLE(r,5)=HOW(task,1);
                            TRUCKTABLE(r,6)=HOW(task,2);
                            %truck unavailable
                            TRUCKTABLE(r,4)=1;
                            %determine the time it will take to load the truck
                            BucketCycleTime=rand([1,BucketsReq]);
                            x=find(BucketCycleTime<Phi);
                            y=find(BucketCycleTime>=Phi);
                            BucketCycleTime(x)=(L+sqrt((M-L)*(U-
L)*BucketCycleTime(x)));
                            %Uh-sqrt((Uh-Mh)*(Uh-Lh)*(1-H))
                            BucketCycleTime(y)=(U-sqrt((U-M)*(U-L)*(1-
BucketCycleTime(y))));
                            loadtime=sum(BucketCycleTime);
                            %indicate excavator is working
                            EXTABLE(EXAVAILABLE(i),7)=1;
```

```
                            %determine  the  time  that  the  truck  will  be  done
loading
                            EET=TNOW+loadtime;
                            %add the finish of the truck loading to the event list
recorded
                            %the equipment then the event type and finally the end
time
                            %100 means truck loaded
                            ADDEVENT=[r,100,EET];
                            EVENTLIST=[EVENTLIST;ADDEVENT];
                            %take away truck load from task
                            EXTABLE(EXAVAILABLE(i),5)=(EXTABLE(EXAVAILABLE(i),5)-
1);
                        end
                    end
                else
                    %find  the  minimum  event  time  on  the  event  list  (newTNOW)  and
what
                    %row of the list it is on (I)
                    [newTNOW,I]=min(EVENTLIST(:,3));
                    TNOW=newTNOW;
                    %assure  that  all  events  are  handled  (possible  that  multiple
events
                    %end at same time)
                    %If the event is truck loaded
                    if EVENTLIST(I,2)==100
                        %calculate distance truck must go to dump
                        truckNo=EVENTLIST(I,1);
                        Dist=GRIDSPACING*sqrt(((TRUCKTABLE(truckNo,5)-
TRUCKTABLE(truckNo,2))^2)+((TRUCKTABLE(truckNo,6)-TRUCKTABLE(truckNo,3))^2));
                        if Dist==0
                            Dist=GRIDSPACING/2;
                        elseif
(TRUCKTABLE(truckNo,5))==666||(TRUCKTABLE(truckNo,2))==666||(TRUCKTABLE(truckNo,6)
)==666||(TRUCKTABLE(truckNo,3))==666
                            Dist=414;
                        end
                        Uh=Dist/400;
                        Mh=Dist/717;
                        Lh=Dist/800;
                        %Truck Haul Time
                        Zeta=(Mh-Lh)/(Uh-Lh);
                        TruckHaulRand=rand(1);
                        if (TruckHaulRand<=Zeta)
                            TruckHaulRand=Lh+sqrt((Mh-Lh)*(Uh-Lh)*TruckHaulRand);
                        else
                            TruckHaulRand=Uh-sqrt((Uh-Mh)*(Uh-Lh)*(1-
TruckHaulRand));
                        end
                        EET=TNOW+TruckHaulRand;
                        %free excavator
                        EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),7)=0;
                        %200 means truck travel loaded
                        ADDEVENT=[truckNo,200,EET];
                        EVENTLIST(I,:)=[];
                        EVENTLIST=[EVENTLIST;ADDEVENT];
                        %check to see if that truckload completes excavators
                        %assigned task
                        if EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),5)==0
                            EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),6)=0;
                            %check to see if excavator can continue task with more
trucks
                        elseif
EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),6)==1                            &&
EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),7)==0
                            %find trucks matched to excavator that are free to be
filled

[r,c]=find((TRUCKTABLE(:,7))==(EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),1))
&(TRUCKTABLE(:,4)==0));
                            if isempty(r)==0
```

```
                                %might  be  more  than  one  truck  available,  start
with first
                                r=r(1);
                                %record destination that truck will take the dirt
                                TRUCKTABLE(r,2)=HOW(task,3);
                                TRUCKTABLE(r,3)=HOW(task,4);
                                %record destination trucks started from
                                TRUCKTABLE(r,5)=HOW(task,1);
                                TRUCKTABLE(r,6)=HOW(task,2);
                                %truck unavailable
                                TRUCKTABLE(r,4)=1;
                                %determine the time it will take to load the truck
                                BucketCycleTime=rand([1,BucketsReq]);
                                x=find(BucketCycleTime<Phi);
                                y=find(BucketCycleTime>=Phi);
                                BucketCycleTime(x)=(L+sqrt((M-L)*(U-
L)*BucketCycleTime(x)));
                                %Uh-sqrt((Uh-Mh)*(Uh-Lh)*(1-H))
                                BucketCycleTime(y)=(U-sqrt((U-M)*(U-L)*(1-
BucketCycleTime(y))));
                                loadtime=sum(BucketCycleTime);
                                %indicate excavator is working

EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),7)=1;
                                %determine  the  time  that  the  truck  will  be  done
loading
                                EET=TNOW+loadtime;
                                %add the finish of the truck loading to the event
list recorded
                                %the equipment then the event type and finally the
end time
                                %100 means truck loaded
                                ADDEVENT=[r,100,EET];
                                EVENTLIST=[EVENTLIST;ADDEVENT];
                                %take away truck load from task

EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),5)=(EXTABLE((EXTABLE(:,1)==(TRUCKT
ABLE(truckNo,7))),5)-1);
                        end
                    end
                    %if the event is truck traveled full
                elseif EVENTLIST(I,2)==200
                    truckNo=EVENTLIST(I,1);
                    %update truck location

TRUCKTABLE(truckNo,3)=EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),3);

TRUCKTABLE(truckNo,4)=EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),4);
                    %calculate distance truck must go to get back to excavator
                    Dist=GRIDSPACING*sqrt(((TRUCKTABLE(truckNo,5)-
TRUCKTABLE(truckNo,2))^2)+((TRUCKTABLE(truckNo,6)-TRUCKTABLE(truckNo,3))^2));
                    if Dist==0
                        Dist=GRIDSPACING/2;
                    elseif
(TRUCKTABLE(truckNo,5))==666||(TRUCKTABLE(truckNo,2))==666||(TRUCKTABLE(truckNo,6)
)==666||(TRUCKTABLE(truckNo,3))==666
                        Dist=414;
                    end
                    Ur=Dist/400;
                    Mr=Dist/717;
                    Lr=Dist/800;
                    %Truck Return Time
                    Beta=(Mr-Lr)/(Ur-Lr);
                    TruckReturnRand=rand(1);
                    if (TruckReturnRand<=Beta)
                        TruckReturnRand=Lr+sqrt((Mr-Lr)*(Ur-
Lr)*TruckReturnRand);
                    else
                        TruckReturnRand=Ur-sqrt((Ur-Mr)*(Ur-Lr)*(1-
TruckReturnRand));
                    end
```

```
                        EET=TNOW+TruckReturnRand;
                        %300 means truck return
                        ADDEVENT=[truckNo,300,EET];
                        EVENTLIST(I,:)=[];
                        EVENTLIST=[EVENTLIST;ADDEVENT];
                        %if the event was return empty
                    elseif EVENTLIST(I,2)==300;
                        truckNo=EVENTLIST(I,1);
                        TRUCKTABLE(truckNo,4)=0;
                        if    EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),6)==1
&& EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),7)==0
                            %find trucks matched to excavator that are free to be
filled

[r,c]=find((TRUCKTABLE(:,7))==(EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),1))
&(TRUCKTABLE(:,4)==0));
                            %might be more than one truck available, start with
first
                            r=r(1);
                            %record destination that truck will take the dirt
                            TRUCKTABLE(r,2)=HOW(task,3);
                            TRUCKTABLE(r,3)=HOW(task,4);
                            %record destination trucks started from
                            TRUCKTABLE(r,5)=HOW(task,1);
                            TRUCKTABLE(r,6)=HOW(task,2);
                            %truck unavailable
                            TRUCKTABLE(r,4)=1;
                            %determine the time it will take to load the truck
                            BucketCycleTime=rand([1,BucketsReq]);
                            x=find(BucketCycleTime<Phi);
                            y=find(BucketCycleTime>=Phi);
                            BucketCycleTime(x)=(L+sqrt((M-L)*(U-
L)*BucketCycleTime(x)));
                            %Uh-sqrt((Uh-Mh)*(Uh-Lh)*(1-H))
                            BucketCycleTime(y)=(U-sqrt((U-M)*(U-L)*(1-
BucketCycleTime(y))));
                            loadtime=sum(BucketCycleTime);
                            %indicate excavator is working
                            EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),7)=1;
                            %determine the time that the truck will be done
loading
                            EET=TNOW+loadtime;
                            %add the finish of the truck loading to the event list
recorded
                            %the equipment then the event type and finally the end
time
                            %100 means truck loaded
                            ADDEVENT=[r,100,EET];
                            EVENTLIST=[EVENTLIST;ADDEVENT];
                            %take away truck load from task
EXTABLE((EXTABLE(:,1)==(TRUCKTABLE(truckNo,7))),5)=(EXTABLE((EXTABLE(:,1)==(TRUCKT
ABLE(truckNo,7))),5)-1);
                        end
                        %delete event
                        EVENTLIST(I,:)=[];
                    end
                end
                %at end of program there will be no more events in the event list.
                %Record the final time.
                if isempty(EVENTLIST)==1;
                    task=MAXTASK+1;
                    Minutes(z)=TNOW;
                    Hours(z)=TNOW/60;
                end
            end
            Hours
        end
        STDEV=std(Hours)
        MEAN=mean(Hours)
```